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ORIGIN OF THE BENDIGO SADDLE REEFS WITH COMMENTS ON THE FORMATION OF RIBBON QUARTZ.[1]

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ABSTRACT.

Several textural varieties of quartz, together with ore textures and structural relations, indicate that (1) open-space filling, (2) replacement, and (3) growth by accretion were active processes in the formation of the saddle reefs and related quartz bodies of the Bendigo goldfield, Australia. The relative importance of each process varied with the type of quartz body: spurs and the central parts of saddle reefs formed by open-space filling; leg reefs, "backs," fault reefs, inner reefs, and some parts of saddle reefs formed by replacement; all types of quartz bodies were affected by the process of accretion, which included intermineralization fracturing, brecciation, vein reopening, and recementation by quartz. Permeability was thereby maintained and deposition of late gold facilitated. The position of the textural varieties of quartz in the fracture pattern, which localized the quartz bodies in the folded rocks, is a key to the type of stress active in the formation of each body and indicates its method of emplacement.

Book structure, ribbon structure, and "crinkly banding" probably resulted primarily from the replacement of previously sheared or foliated zones in wall rock; the individual leaves and ribbons are usually residues

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from the replacement process. In addition to replacement at Bendigo, dilation of foliated rock by spreading of leaves and ribbons probably took place. The subsequent deposition of quartz in the open spaces resulted in laminated structures. Spreading apart of the foliation planes occurred along bedding-plane faults as a consequence of tensional stresses which resulted from the reverse faulting superimposed on the folded rocks.

INTRODUCTION.

Book structure and ribbon structure, commonly found in gold-quartz veins, have been explained by several alternative hypotheses. These hypotheses were reviewed in a recent paper by McKinstry and Ohle,[2] and evidence was presented which indicates that at Alleghany, California; Porcupine, Ontario; Bendigo, Victoria, and elsewhere, these structures are gradational in nature and are probably formed by the "deposition of quartz or other gangue material in a zone which is already sheeted, schistose or sheared." According to this explanation, the individual laminae of wall rock and ribbons of chlorite, sericite, carbonaceous material, sulfides, or "fossil slickensides" are residues that survived replacement by quartz. The replacement process, therefore, in their opinion, more adequately accounts for the features present in laminated[3] quartz veins than do the other hypotheses.

This interpretation is contrary to that of Ransome,[4] Hulin,[5] Hurst,[6] Johnston,[7] Farmin,[8] and Taber[9] and others who have variously attributed book structure and ribbon structure either to (1) accretion, (2) post-quartz shearing, (3) inflation of rock structure by invading solutions, or (4) force of growing crystals. The most widely held view is that these laminated structures were produced by accretion which resulted from successive reopenings of the vein fissures more or less contemporaneously with the deposition of quartz in open spaces.

The conclusions of the writer, based on observations made during two years' detailed mapping and study in the Bendigo goldfield (where laminated quartz is unusually prominent) and on many less detailed observations in California and Ontario, in general agree with the conclusions of McKinstry and Ohle.

[2] McKinstry, H. E., and Ohle, E. L., Jr., Ribbon structure in gold quartz veins: Econ. Geol., vol. 44, pp. 87–109, 1949.

[3] The definitions of book structure, ribbon structure, laminated structure, leaves, laminae, and ribbons proposed by McKinstry are followed in this paper. These terms pertain to the banded or streaked nature of many gold quartz veins where the banding is due to "slabs or films of country rock or other material interlayered with quartz. When the bands are relatively thick—from a millimeter to several centimeters—and the material of which they are composed is definitely recognizable as country rock, the aggregate is commonly called *book structure*. When they are thin films or septa lacking the texture or appearance of country rock the term used is ribbon structure." Laminated structure is used as an inclusive term to describe both book and ribbon structure.

[4] Ransome, F. L., Mother Lode district, California: Geologic Atlas of the United States, U. S. Geol. Survey, Folio No. 63, 1900.

[5] Hulin, C. D., Structural control of ore deposition: Econ. Geol., vol. 24, pp. 15–49, 1929.

[6] Hurst, M. E., Vein formation at Porcupine: Econ. Geol., vol. 30, pp. 103–127, 1935.

[7] Johnston, W. D., Jr., Vein-filling at Nevada City, California: Geol. Soc. America Bull., vol. 49, pp. 23–34, 1938.

[8] Farmin, Rollin, Host-rock inflation by veins and dikes at Grass Valley, California: Econ. Geol., vol. 36, pp. 143–174, 1941.

[9] Taber, S., Discussion: Econ. Geol., vol. 13, pp. 538–546, 1918.

Evidence of replacement in gold-quartz veins in general and in laminated quartz veins in particular is usually present. The structures and textures observed by the writer indicate that both book structure and ribbon structure resulted primarily from the replacement of previously sheeted, sheared, schistose, or foliated zones in wall rocks and that the individual leaves or laminae are usually residues from the replacement process. In addition to replacement, however, dilation of foliated rocks, by spreading of leaves and ribbons along bedding plane faults, probably took place. The subsequent deposition of quartz in open spaces resulted at least locally in laminated structure.

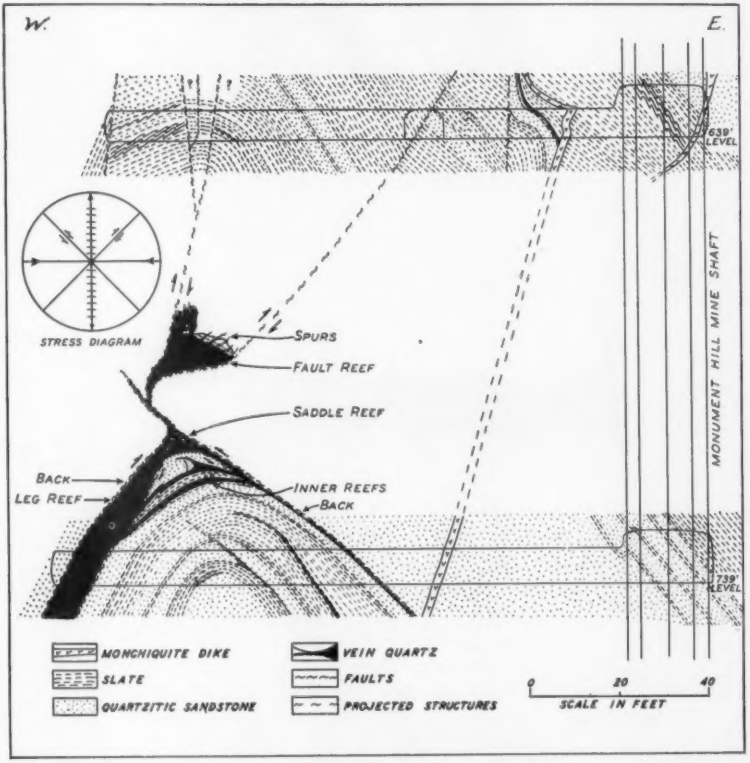

FIG. 1. Cross section of a part of the Deborah anticline in the Monument Hill mine, showing in detail a typical fold in slate and quartzite with superimposed bedding plane and crosscutting faults, a monchiquite dike, and several types of quartz bodies, including saddle reefs, leg reefs, inner reefs, "backs" and spurs. The geology shown between the levels, except where indicated by the longer dashed lines, was well exposed in raises and stopes, and was originally mapped in section on a scale of 1 inch equals 20 feet.

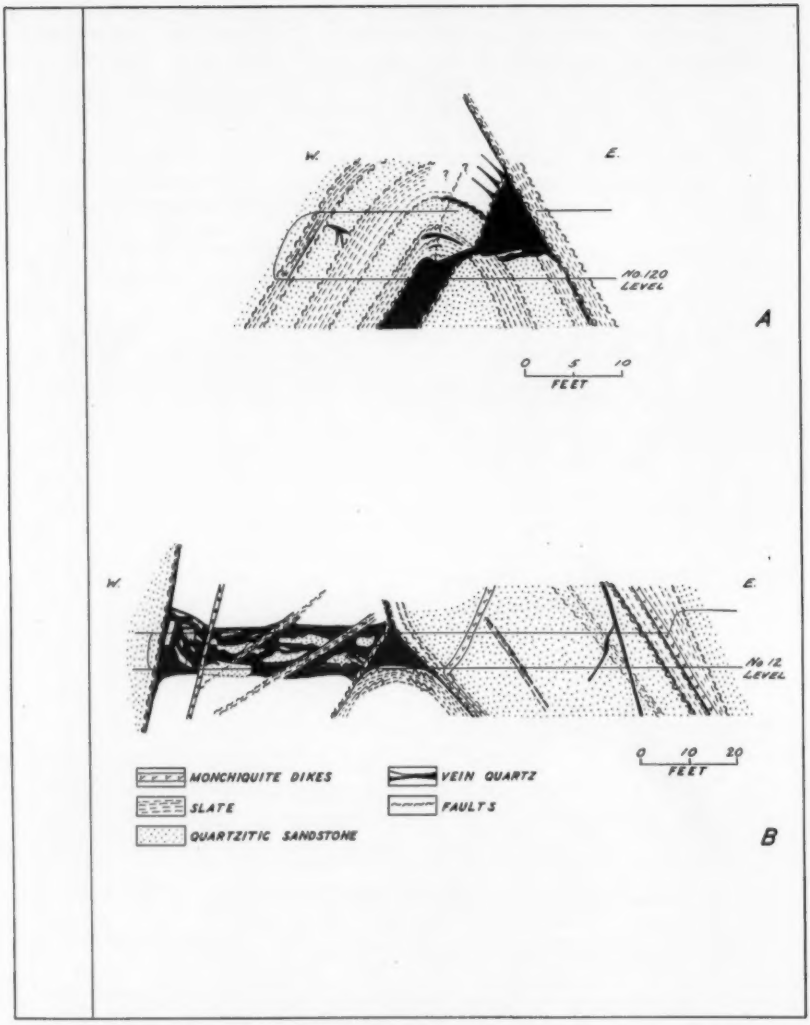

FIG. 2. A. Cross section of the upper part of a leg reef and a spur reef that formed below the intersection of a crosscutting fault and a bedding-plane fault of opposite dip. Minor bedding-plane and crosscutting veins are shown. West crosscut, 120 level. Central Nell Gwynne mine, Bendigo. B. Cross section of a saddle reef at the crest of the Deborah anticline and an irregular replacement quartz body, with many large wall-rock inclusions, between a strong west-dipping bedding-plane fault and the center of the anticline. Other bedding-plane and crosscutting quartz veins are shown on the east limb of the fold. West crosscut, No. 12 level, Monument Hill mine, Bendigo.

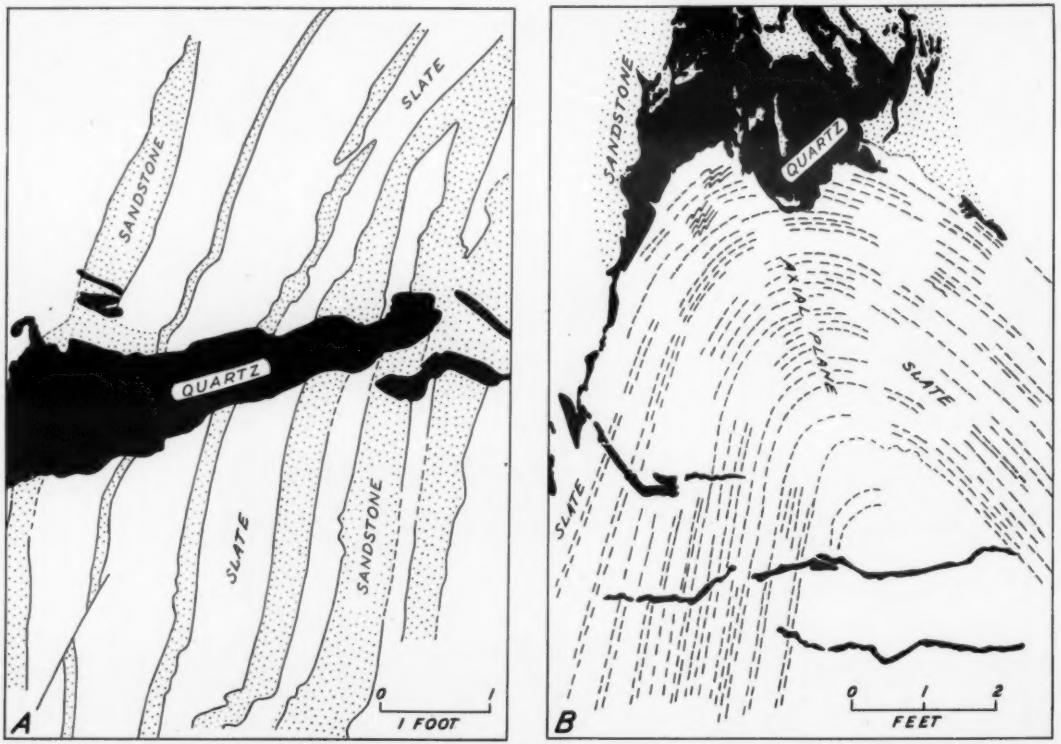

FIG. 3. A. Cross section showing flatly dipping quartz spurs crosscutting steeply dipping slate and sandstone beds. 520 level, Johnson's Reef, No. 1 mine, Garden Gully Line of Reef. Source: Sketched from Plate 17A, "Reports on the Bendigo gold field," by E. J. Dunn, 1896. B. An irregular replacement quartz body at the crest of the Garden Gully anticline with irregular, horizontal spurs in the slate. 520 ft. level, Johnson's Reef, No. 1 mine, Garden Gully Line of Reef. Source: Sketched from Plate 17B, "Reports on the Bendigo gold field," by E. J. Dunn, 1896.

FIG. 4. A typical saddle reef with triangular cross section formed below the intersection of east- and west-dipping bedding-plane faults. Note the curved drag on the west-dipping fault on the left. The saddle reef is bottomed by the "turn over" of bedding at the crest of the Deborah anticline (not shown). The milky white quartz is somewhat vuggy and contains numerous partly replaced fragments of slate which in places are coated by a thin crust of ankerite. Intermineralization fracturing is indicated by the numerous sheetlike fractures roughly parallel to the west-dipping fault; some of these are followed by clear quartz of a second generation. Gold content here was low. Monument Hill mine, 712 ft. Int. level. Deborah Line of Reef.

FIG. 5. An asymmetrical saddle reef. The hanging wall of the quartz body is limited by a strong pre-quartz, west-dipping strike fault; the footwall by the "roll over" of the Deborah anticline. Here there is no east-dipping "matching back" or bedding-plane fault to intersect the west-dipping fault above the arch of the fold. The quartz body, therefore, is asymmetrical in cross section. This reef formed partly by replacement and partly by open-space filling. The laminated quartz vein, 8 to 10 inches thick, which follows the arch of the fold (left center) formed by replacement of a bedding-plane fault that curved over the crest of the fold; the zone of black slate inclusions (a coarse variety of "magpie" quartz) 4 feet thick (above the arch) formed primarily by replacement of a fractured and brecciated slate bed; the white, massive, "bull" quartz 3 to 15 feet thick formed by open-space filling, as is indicated by the large vugs lined with euhedral quartz crystals and the coarse texture of the quartz. Some replacement took place in the "bull" quartz as is shown by dark, irregular inclusions partly replaced by quartz. Monument Hill mine, 640 level. Deborah Line of Reef, Bendigo.

FIG. 6. A typical "leg reef." Laminated quartz, 1 to 2 feet wide, following a strong bedding-plane fault with a slate footwall and sandstone hanging wall. More than one period of movement and quartz deposition is indicated by the strong shear plane which is made up of graphitic slips and gouge on the hanging wall of the main body of quartz. Later quartz in narrow, discontinuous veinlets and in prominent book structure follows the hanging-wall fault. Note drifter and crossbar for scale. Monument Hill mine, No. 12 level, north drive on west leg reef.

FIG. 7. Quartz spurs in the footwall of a "back," *i.e.*, a bedding-plane fault followed by laminated quartz. The flatly dipping veins or spurs (25°–30° W) are in places wedge-shaped and follow tensional openings that formed in the footwall of the bedding-plane fault. In places gold is localized at the junction of the laminated quartz with the spurs. Scale: width of view about 6 feet. No. 6 level, Nell Gwynne (B.M.L.) mine, Bendigo.

FIG. 8. Selective replacement by quartz of a dragged, folded slate bed at the crest of the Deborah anticline, forming an "Inner Reef." Fig. 17 is a photograph of a specimen from this exposure. Scale: width of view about 4 feet. No. 11 level, Monument Hill mine.

FIG. 9. Vug with euhedral quartz crystals in coarse massive quartz. Specimen from the center of a saddle reef. An altered wall-rock inclusion is embedded in the massive quartz on the left side of the specimen. Central Nell Gwynne mine, 820 ft. level. Scale in inches. Nell Gwynne Line of Reef.

FIG. 10. Strong bedding-plane fault (or "back") with characteristic laminated quartz (6 inches wide) containing free gold. A post-quartz monchiquite dike occurs on hanging wall of the laminated quartz. Two periods of movement took place on this fault; each was followed by the deposition of laminated quartz. Scale: note size of drill steel. Photograph of a dike and a laminated quartz vein which is shown in the level station (plat) at east end of the cross-cut shown in Fig. 2B. No. 12 level, Monument Hill mine.

FIG. 11. Typical "book structure" from a Bendigo "back" with laminated graphitic slate and quartz. See photomicrographs of thin sections, Figs. 32 and 33. Scale in inches. Ironbark mine, Sheepshead Line of Reef.

FIG. 12. Typical "book structure" with parallel bands of quartz and graphitic slate. Specimen from the wall of a strong, west-dipping bedding-plane fault. Thin crusts of ankerite coat the slate laminae in the quartz band on the side of the specimen opposite the scale. Specks of native gold occur along contact between ankerite and quartz. Scale in inches. Alliance mine, No. 8 level. Bendigo, Victoria.

FIG. 13. Book structure from a typical Bendigo "back" with leaves of slate (black) and quartz (white). Note the discontinuous slate laminae that end abruptly against quartz; also note the two parallel laminae that trend diagonally across a quartz band and that have been ruptured by spreading. Scale: Divisions on scale are 0.1 inch.

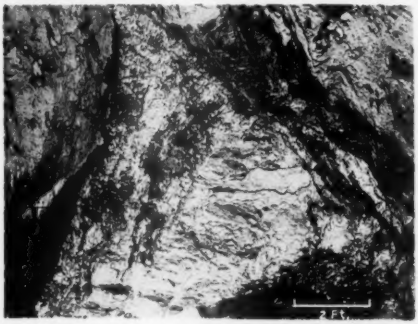

FIG. 4

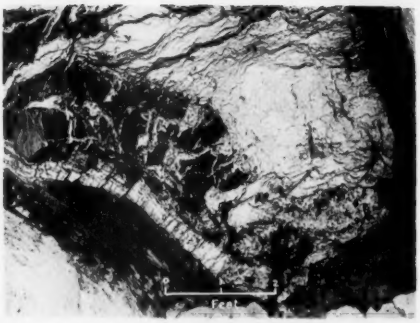

FIG. 5

FIG. 6

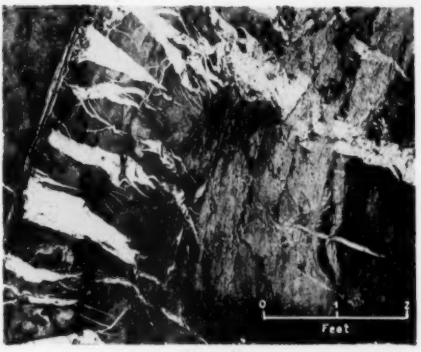

FIG. 7

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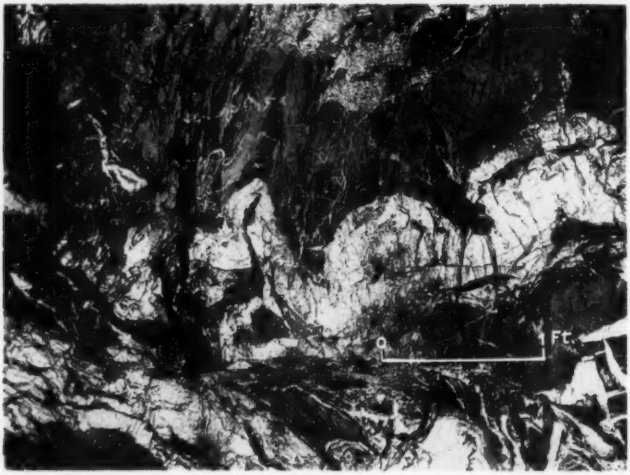

FIG. 8

FIG. 9

FIG. 10

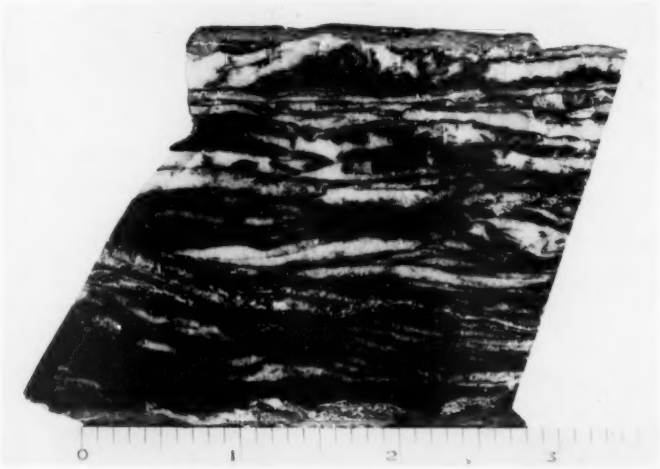

FIG. 11

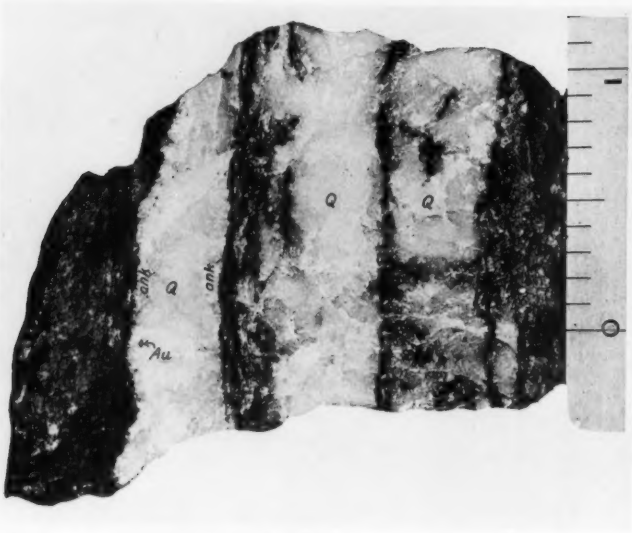

FIG. 12

FIG. 13

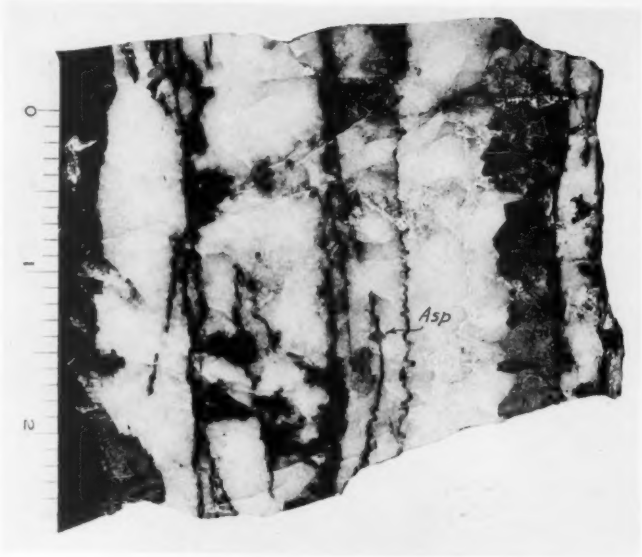

FIG. 14

FIG. 15

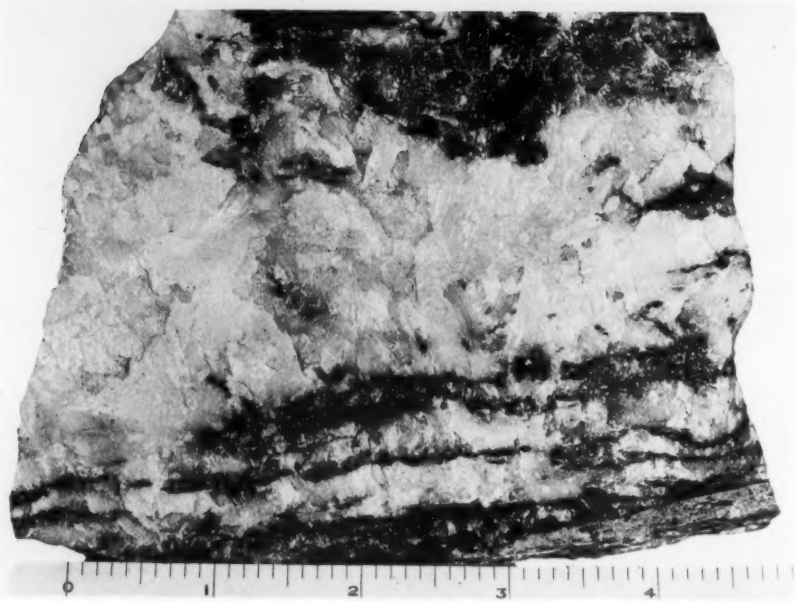

FIG. 16

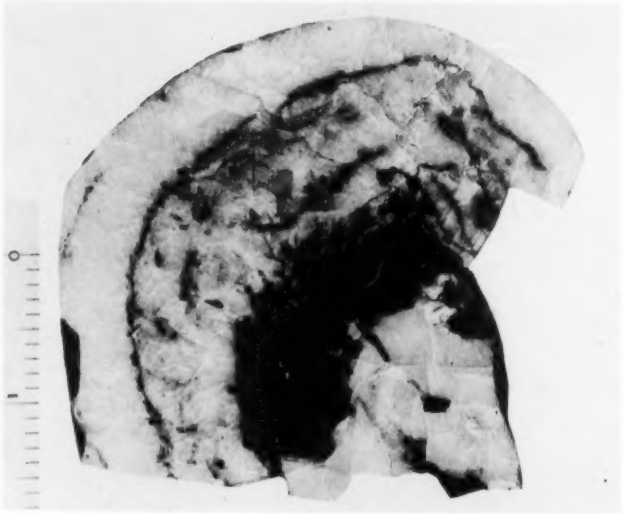

FIG. 17

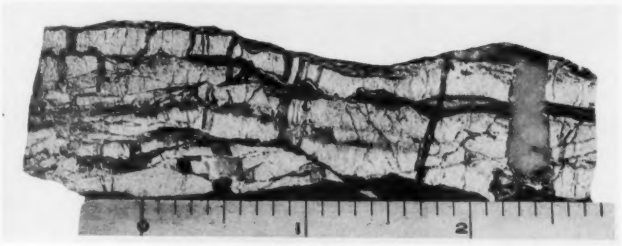

FIG. 18

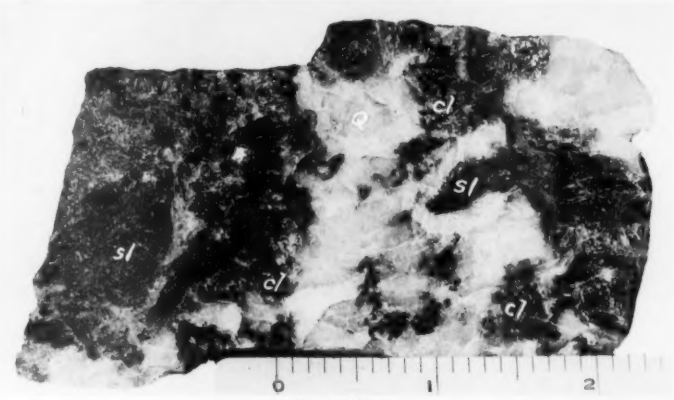

FIG. 19

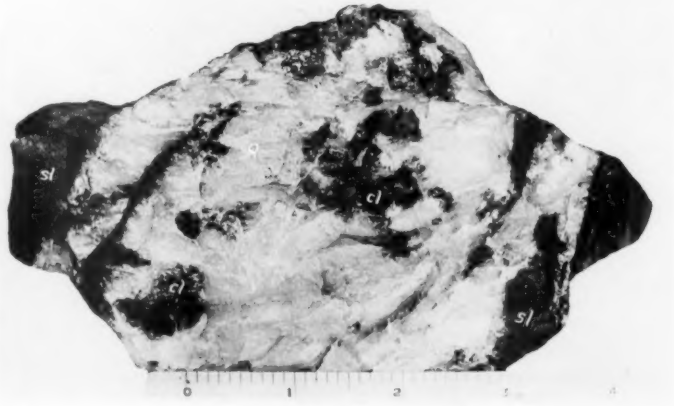

FIG. 20

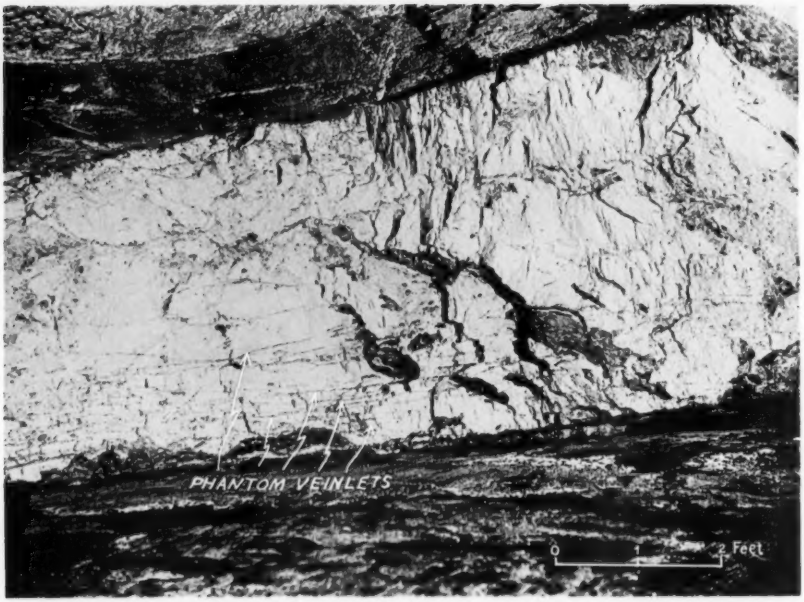

FIG. 21

FIG. 22

Replacement, therefore, in the writer's opinion, is in places accompanied by open-space filling; and it may not be possible to tell where open-space filling ends and replacement begins. Definite evidence of both of these processes may exist in the same vein, and even in the same hand specimen, but the relative amount of each may be indeterminate.

In addition to replacement and open-space filling, vein formation by accretion has played an important part in the origin of many quartz bodies.[10] Abun-

[10] Strictly defined, vein formation by accretion involves open-space filling, for the process, according to Hulin, consists of ". . . the repeated filling of small openings produced recurrently by intermineralization fault movements . . . (and) the alternate brecciation of previously de-

FIG. 14. Typical ribbon structure with quartz, slate, chlorite, and arsenopyrite ribbons. Stylolitelike "crinkly bands" are prominent. Crinkly bands are jagged, like the curves of a seismogram. Scale in inches. Red, White and Blue mine. 1530 level, Sheepshead Line of Reef.

FIG. 15. An enlargement of part of Fig. 14 to show "crinkly bands" in detail. Note the arsenopyrite crystal cutting across a "crinkly band."

FIG. 16. Typical ribbon structure along the wall (bottom, next to scale) of a gold-bearing quartz vein. The laminations are parallel to bedding and a bedding-plane fault, and consist of slate and carbonaceous leaves with "fossil" slickensides and graphitic slips. Near the wall the laminae are definitely slate leaves, whereas those away from the wall are graphitic or carbonaceous ribbons. The specimen shows a gradation from "book structure" to "ribbon structure." Replacement origin of the laminae is suggested by the discontinuous lines of inclusions with quartz bridges; the quartz has the same color and texture, and is the same age on both sides of the laminae. Scale in inches.

FIG. 17. A replaced drag fold with ribbon structure. Note residues of slate in quartz. The crenulated ribbon of dark graphitic material is the preserved part of a graphitic, bedding-plane slip that probably developed during drag folding of the slate. See Fig. 8 for photograph of underground exposure from which this specimen was collected. Scale in inches. Monument Hill mine, No. 11 level. Deborah Line of Reef.

FIG. 18. Laminated slate and ankerite with later cross veinlets of quartz forming a ladder structure. Specimen from an east-dipping "back," 5 inches wide. Specimen was etched with dilute HNO_3 to emphasize ankerite. Scale in inches. No. 6 Plat, Nell Gwynne (B.M.L.) mine, Nell Gwynne Line of Reef.

FIG. 19. Chloritic quartz showing replacement of slate by chlorite, and chlorite by quartz. Scattered grains of sphalerite and galena replaced both quartz and chlorite. Scale in inches. 820 ft. level, Central Nell Gwynne mine, Nell Gwynne Line of Reef.

FIG. 20. Magpie quartz. Massive coarse quartz with scattered fragments of slate. The slate has been partly to wholly replaced by chlorite; quartz in turn replaced the chlorite. In a few places chlorite remained as greenish ghosts in the quartz. Specimen was from a strong, 1–3 foot wide, west-dipping "back." Scale in inches. 820 level, west crosscut, Central Nell Gwynne mine. Nell Gwynne Line of Reef.

FIG. 21. Massive white quartz of a strong leg reef cut by sheetlike fractures parallel to the vein walls. Some, but not all, of these fractures have been cemented by a water-clear, fine-textured quartz that forms phantom veinlets. Underground photograph looking vertically up at the back of a drift. Scale: vein is about 4 feet wide. No. 688 Intermediate level. Monument Hill mine. Deborah Line of Reef.

FIG. 22. Phantom veinlets. Diagonal, en echelon gash veinlets of clear "watery" quartz filling tension fractures in milky quartz. Scale divisions are 0.1 inch. No. 688 Intermediate level. Monument Hill mine.

dant evidence is present in the Bendigo saddle reefs, as well as in many quartz veins elsewhere, of repeated movement along the walls of laminated quartz veins accompanied by reopening of the vein fissure and subsequent deposition of quartz or carbonates in two or more parallel, subparallel or even cross-cutting veins. Thus laminated structure itself probably results primarily from replacement, whereas the vein as a whole may be made up of two or more layers of laminated quartz which resulted from growth by accretion.

It is concluded from a detailed structural and textural study that the Bendigo saddle reefs and related quartz bodies were complex in origin, and that all three processes—open-space filling, replacement, and growth by accretion—were operative in their formation, with the relative importance of the individual processes varying from place to place in an individual body and in the district as a whole.

The purpose of this paper is to present the evidence from Bendigo on which the above conclusions are based. Because the origin of laminated quartz at Bendigo cannot properly be considered apart from the origin of the saddle reefs themselves, both are presented here as one more or less related topic. Much of the evidence and some of the views have been published elsewhere by others; here an attempt is made to describe the pertinent features and to present a unified interpretation of the origin of the Bendigo saddle reefs and the formation of laminated quartz.

SUMMARY OF BENDIGO GEOLOGY.

The general geologic environment and characteristics of the gold quartz bodies of Bendigo are well known through the work of Rickard,[11] Dunn,[12] Herman,[13] and Stillwell,[14] and in more recent years from the publications of Stone[15] and McKinstry.[16] Only a summary of the features pertinent to the present problem are given in this paper, to provide background for more detailed study of laminated quartz and the origin of the saddle reefs.

The Bendigo gold-quartz deposits are located in an area of fairly uniform, interbedded slates and quartzitic sandstones of Lower Ordovician age, which are more than 5,000 feet thick. These rocks have been folded into a series of roughly parallel anticlines and synclines which strike about N. 15° W. Many of the folds persist for several miles along their strike. In the New Chum Railway mine, deepest of the Bendigo mines, the folds have been followed along

posited vein matter followed by recementation and filling of the open spaces." The important point is that the open space filling is accompanied by recurrent fracturing, brecciation and recementation.

See Hulin, C. D., Structural control of ore deposition: Econ. Geol., vol. 24, p. 23, 1929.

[11] Rickard, T. A., The Bendigo goldfield: Am. Inst. Min. Eng. Trans., vol. 20, 1891.

[12] Dunn, E. J., Reports on the Bendigo goldfield (Nos. I and II): Victoria Dept. of Mines, 1896.

[13] Herman, H., Economic geology and mineral resources of Victoria: Victoria Geol. Survey Bull. 34, 1914.

[14] Stillwell, F. L., The factors influencing gold deposition in the Bendigo goldfield (parts I, II, III): Commonwealth of Australia Advisory Council of Science and Industry Bulls. 4, 8, 16, 1917, 1918, 1919.

[15] Stone, J. B., The structural environment of the Bendigo goldfield: Econ. Geol., vol. 32, no. 7, pp. 867–895, 1937.

[16] McKinstry, H. E., Bendigo, Victoria, Australia. Ore Deposits as Related to Structural Features, pp. 160–162, ed. by W. H. Newhouse, Princeton Univ. Press, Princeton, N. J., 1942.

the axial planes to a vertical depth of 4,600 feet. The folds are of the similar type with the axial planes inclined, generally eastward, from vertical to 75°. Individual folds are unusually sharp, with the "turn over" or arch taking place in a width of 25 to 30 feet; the limbs dip uniformly 65° to 75° east and west, and the distance from fold crest to fold crest varies from 400 to 1,600 feet, with the average about 900 feet. Along the strike of the axes, the folds have a pronounced plunge, locally up to 30°. In general, at the north end of the gold field the folds plunge north, and at the south end the folds plunge south. This reversal in plunge resulted in a group of gentle domes which trend obliquely across the gold field. The more productive ore bodies have been found along the anticlines in the area of the domes, particularly where the plunge is to the north.

Small, but persistent, post-quartz, lamprophyre dikes follow the axial planes and limbs of the folds and are the only igneous rocks in the district. These vary from paper-thin dikelets to dikes 15 feet wide; the average is between 1 and 2 feet. The north contact of the Harcourt granodiorite stock is 8 miles south of the center of the gold field and may possibly underlie the district at no great depth. The granodiorite intrudes the sedimentary series and cross-cuts the axial planes of the folds without noticeable disturbance. It is considered to be post-Ordovician in age, probably Devonian.

In the mineralized area pre-mineral faults are abundant. A few oblique faults, locally called "cross-courses," cut across the strike and dip of bedding and across fold axes. More numerous and more important, because they have localized the gold-bearing quartz bodies, are strike faults parallel to bedding and approximately parallel to the axial planes of the folds. These faults occur in well-defined fracture systems superimposed on the folded rocks, particularly on the anticlines, where the faults are most abundant. They are reverse faults marked by gouge, slickensides, mullion, and graphitic slips, and in places have striations trending in several directions superimposed on one another, indicating that movement was repeated several times or was oscillatory.

The bedding-plane faults, with an average dip of 70°, follow the limbs of folds parallel to bedding. They tend to die out in depth as bedding plane slips, but upward toward the crest of the folds, they increase in strength and as the bedding flattens with the turnover of the folds, the faults cut across bedding, flatten in dip to about 45° and die out in a few feet. The stronger, more persistent faults, however, displace the axial planes of the folds from a few inches to many feet, and in places continue across the folded beds to the adjacent fold. These faults are persistent parallel to the strike of the fold axes; the more weakly developed ones usually extend several hundred feet, whereas the major ones have been followed by mine workings for several thousand feet.

The bedding-plane or strike faults tend to occur in pairs (locally called "matching backs") at the same stratigraphic horizon, thus forming a conjugate system with nearly parallel strike and opposite dip, one set dipping west and the other east, parallel to the limbs of the fold with which they are associated. In places these meet over the crest of a fold; there one fault is commonly cut off and dragged by the other, with the stronger fault displacing the anticlinal axis from a few feet to several tens of feet.

Many maps and sections have been published that illustrate the characteristics of the Bendigo folds, faults, and quartz bodies. Most of these, however, are on a small scale and are considerably generalized. Figure 1, a cross section of a part of the Deborah anticline where it is well exposed in the Monument Hill mine, shows in detail the features of a typical fold, the vagaries of superimposed faults, and a cross-cutting monchiquite dike, as well as several types of quartz bodies that were well-exposed in raises and stopes at the time of the mapping. Figures 2 and 3 show some of the characteristic structures of the gold field.

GOLD–QUARTZ BODIES.

The gold-bearing quartz bodies of Bendigo occur in a variety of shapes and forms, which were due primarily to the influence of the pre-mineral folds and faults. These forms include, according to local terminology, saddle reefs, fault reefs, leg reefs, neck reefs, trough reefs, and spurs.

Curiously, the Bendigo saddle reef, as it is now understood, rarely if ever conforms to the early (classic) simple description. It has been described as a saddle-shaped mass of quartz, conformable to bedding, that formed by open-space filling at the crest of an anticline or trough of a syncline where slipping of alternate beds in the folded rocks had created an open space.[17] Although the saddle shape is roughly approximated in many places the common quartz body has a more complex form, and those bodies approaching the shape of a true saddle reef probably were in no place due to open-space filling in the original sense, but rather formed by selective replacement of a folded slate or quartzite bed.

The ideal saddle reef, as it is now defined, formed at the crest of an anticline where two strike faults of opposite dip (i.e., "matching backs") intersected above the crest of an anticline. The quartz body localized in this way is roughly triangular in cross section, but has a curved lower limit parallel to the arch of bedding as it forms an anticlinal fold. The upper part of such a body is shown in Figure 4. Many saddle reefs are asymmetrical in outline, and have a single strike fault forming the hanging wall with the footwall limited by a part of the anticlinal fold in such a way that the quartz body is slightly off-center (Fig. 5).

The lower part of the ideal saddle reef follows the bedding-plane fault down each limb of the fold, and where well developed as a bedded vein it is known as a "leg reef" (Fig. 6). On the other hand, a quartz vein along a strong strike fault above the crest of a fold where it cross cuts bedding is called a "neck reef."

Quartz bodies localized solely by reverse faults with no apparent relation to bedding or folding are called "fault reefs." These are more common in Bendigo than is generally realized and are usually associated with quartz spurs.

Quartz spurs, or spur reefs, as they are sometimes called, are irregular to wedge-shaped bodies of quartz that are usually flat in dip and cut indiscriminately

[17] Dunn, E. J., Reports on the Bendigo gold field (Nos. I and II): Victoria Dept. of Mines, 1896.

Rickard, T. A., The Bendigo gold field: Am. Inst. Min. Met. Eng. Trans., vol. 20, pp. 463–545, 1891; also, Origin of gold-bearing quartz of Bendigo reefs: Idem., p. 289, 1893.

across bedding. Most spurs occur in a set of quartz-filled tension fractures. Two types are recognized: (a) systems of more or less horizontal gash veins that formed in the footwall of a strong-bedding plane fault, and cut across steeply dipping sandstone or slate (Figs. 3A, 3B and 7) and (b) gash veins and irregular masses of quartz, in places of considerable size, that formed along the intersection of a bedding-plane fault and a strike fault of opposite dip. Veins of the second type are generally found in an east-dipping quartzitic sandstone where it has fractured in a series of en échelon breaks. These spurs have been the source of much gold, particularly around the outer limits of the district.

The Bendigo quartz bodies, where well developed in the central part of the gold field, are generally complex, with several reef types present. A saddle reef, a fault reef, a leg reef, narrow-bedded veins, an inner reef, and spurs, for example, were revealed by detailed mapping of a part of the Monument Hill mine (Fig. 1). Such occurrences are probably the rule rather than the exception.

The anticlinal saddle reefs are usually 10 or 20 feet high and a few larger ones attain 100 feet or more. Along the plunge of the folds the reefs extend from a few tens of feet to several thousand feet; a few have been followed for 9,000 feet. In vertical section the saddle reefs and satellitic bodies tend to repeat one beneath the other, following the repetition of the superimposed fracture systems. In the New Chum mine, for example, 30 saddle reefs were found between the surface and the 2,300-foot level along the axial plane of the New Chum anticline.

MINERALOGY.

The Bendigo reefs are made up predominantly of coarse, massive, grayish-white "bull" quartz which usually contains many dark, angular to rounded fragments of brecciated slate or quartzitic sandstone or is intergrown with parallel layers of slate forming laminated quartz including ribbon structure and book structure. Because of their significance in the vein-forming process, the several varieties of quartz will be described later in some detail.

Other gangue minerals of the district include ankerite, chlorite, and small amounts of sericite and calcite, and rarely albite. Ankerite is abundant throughout the district, particularly as crusts or borders ⅛- to ½-inch thick around the margins of saddle reefs and spurs and surrounding rock fragments within larger masses of quartz. Chlorite is locally abundant and, together with a relatively small amount of sericite, replaced slate and quartzitic sandstone. Calcite, siderite, and albite are found in small amounts in some of the quartz bodies.

The sulfide minerals include pyrite, arsenopyrite, galena, sphalerite, chalcopyrite, and pyrrhotite. These opaque minerals make up 1 to 2 per cent of the ore mined and usually contain a small amount of fine-grained gold. Pyrite is usually the most abundant sulfide, but in places arsenopyrite is more plentiful. Both occur in euhedral crystals disseminated through the quartz bodies and in the slate or sandstone wall rocks around the fringes of the quartz bodies. Locally they are in massive aggregates along the vein walls, around or in in-

clusions, and as laminae in ribbon quartz. Native gold is commonly coarse-grained; in many places it is associated with the sulfides, particularly arsenopyrite and galena; in other places it occurs around the edges of inclusions, along leaves or ribbons in the laminated quartz, and as individual coarse particles in massive quartz of the spur reefs.

TYPES AND SIGNIFICANCE OF QUARTZ.

Quartz in several varieties and textures is the dominant vein mineral of the Bendigo district and makes up the greater part of the saddle and fault reefs, the spurs, and the other more irregular bodies. Although gradational in nature, seven distinctive textural varieties of quartz have been identified megascopically. Two or more of these varieties may be present in a single specimen, and all may be observable underground in a well-exposed quartz body. The varieties include: (1) massive, coarsely crystalline quartz; (2) vug and drusy quartz; (3) laminated quartz, including "book structure" and "ribbon structure" with related "crinkly banding"; (4) magpie quartz, chloritic quartz, and mottled quartz, varieties depending on the nature and distribution of wall-rock inclusions in vein quartz; (5) sheared quartz; (6) brecciated quartz; (7) phantom veinlets.

(*1*) *Massive quartz.*—Coarsely crystalline, massive quartz, similar to that found in gold-quartz veins throughout the world, makes up a large part of both the gold-bearing and the barren quartz bodies of Bendigo. The massive quartz varies considerably in color and texture and commonly grades into other varieties. Clear, glassy quartz with a vitreous lustre is common, as is milky-white quartz. In other places, the quartz is darkened to gray, black, and green by carbonaceous material, chlorite, or other inclusions of various types and sizes. Much of the massive quartz is made up of coarse anhedral crystals with an interlocking granular texture. In places, particularly in the vicinity of vugs, subhedral to euhedral crystals are abundant.

A large part of the central portion of the saddle reefs, all of the spur reefs, and the central parts of the larger fault and leg reefs are composed of massive quartz. Quartz of this type formed both by open-space filling and by replacement. Where quartz cements angular fragments of slate and sandstone in the saddle reefs and spurs, and where it surrounds vugs, it was deposited in open spaces; where it contains ghosts and relics of partly digested wallrock, inclusions of carbonaceous material, and chlorite particles, it formed by replacement.

(*2*) *Vug, druse, and comb quartz.*—Open vugs lined with coarse, euhedral quartz crystals are common in certain parts of the Bendigo quartz bodies, particularly in the heart of the saddle and fault reefs, and in places in the spur reefs. They are rare or nonexistent in the leg-reefs and "backs." The vugs vary from 0.1 inch across to one or more feet wide and two or more feet long. The euhedral crystals vary in size with the size of the vugs; the larger crystals are seldom over 4 or 5 inches long and commonly are imperfect.

Some vugs are coated with parallel growths of quartz crystals with their C axes perpendicular to the vug walls in true comb texture, but crystals pro-

jecting into vugs at random angles are more common. An example of the latter type is illustrated in Figure 9. In this characteristic type the crystals project out of the surrounding massive quartz and do not coat the vug walls.

The presence of vug, druse, and comb texture in the structural environment provided locally at Bendigo is good evidence of open-space filling during mineral deposition. This texture does not always prove open-space filling, however, for both unlined cavities and crystal-lined cavities are found in replacement deposits where they probably indicate that solution and deposition were not exactly balanced during the replacement process. It is possible that some of the vugs and druses in certain parts of the Bendigo quartz bodies are of this origin, but those in the centers of the saddle reefs and in the spur reefs are certainly indicative of open space deposition.

(*3*) *Laminated quartz.*—Laminated quartz, including "book structure" and "ribbon structure," with all gradations between them, is a prominent feature of the Bendigo quartz bodies and is particularly important because much of the gold is associated with quartz of this type. Closely allied types, sheared quartz and "crinkly banding," are likewise abundant. The laminated structure is best developed in the "backs" and "leg" reefs where in places it makes up the full width of the bedded veins; in other places, where the veins are wide, the laminations follow the walls only, and the center of the vein is made up of massive quartz; elsewhere the laminations are more abundant on one wall than on the other or are developed on one wall only. The laminae in the leg reefs and "backs" are parallel, or nearly parallel, to the fault walls and, therefore, to bedding. Figures 6 and 7 show the characteristic features of the laminated quartz in underground exposures. The laminated structure extends up the "backs" and "leg" reef to the place where they merge with a saddle reef proper. Here the laminations tend to split, one part following the strike fault, which forms the hanging wall of the saddle reef, and the other part following the footwall of the reef, curving with bedding as it arches over the anticline. Where strike faults continue beyond the crest of an anticline and are accompanied by a neck reef, the laminated structure is usually prominent and resembles that in the leg reefs, with the difference that here the laminae are not necessarily parallel to the bedding. Figure 4 shows the laminated structure along the hanging wall of a saddle reef and Figure 6 shows ribbon and book structures following the arch of an anticline along the footwall of a saddle reef.

In detail the laminated structure is made up of interlayered leaves or ribbons of quartz and black slate, or slaty residues, forming either book structure or ribbon structure. The leaves are slabs, slivers, or bands of slate, invariably having polished surfaces as graphitic slips or slickensided surfaces. The ribbons, on the other hand, are thin films of slaty material, discontinuous lines, or dashes of carbonaceous material. Typical book structure is illustrated in Figures 11, 12, 13; and ribbon structure in Figures 14, 15, 16, 17. Locally, arsenopyrite or pyrite forms leaves or ribbons as shown in Figure 14. In a few places laminated structure, consisting of slate, quartz, and ankerite bands, has been observed (Fig. 18).

The generalization made by McKinstry and Ohle [18] that there are all grada-

[18] Op. cit.

tions between book structure and ribbon structure is abundantly demonstrated at Bendigo. Traced laterally, many of the slate leaves, in a well-defined book structure, grade from ¼ inch or more wide down to paper-thin ribbons of slaty films or barely visible, dark carbonaceous bands to form ribbon structure. A similar gradation is commonly present inward from the vein walls. Adjacent to the walls the leaves are wider and more numerous, and are definitely recognizable as slate; away from the walls the quartz bands grow wider, and the slate leaves become so narrow that they are no longer identifiable as slate, but become slaty films, discontinuous lines of residual carbonaceous material, tiny linear inclusions, and ghosts of the original leaves (Fig. 16).

Where the leaves grade into ribbons and then into thin, discontinuous lines, they become more irregular and sinuous and depart more and more from parallelism with the vein walls and each other until where developed in extreme they are intricately crenulated. These stylolite-like ribbons at Alle-

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FIG. 23. Phantom veinlets, arranged en echelon, cutting turbid quartz. Photomicrograph. Plain light.

FIG. 24. Domino breccia. Brecciated slate cemented by ankerite from a "back" or bedding-plane fault. The black slate fragments were broken and then rotated or jumbled before being cemented by ankerite. Scale in inches. No. 11 level, Monument Hill mine.

FIG. 25. Quartz-ankerite vein, with matching walls, cutting quartzite. Small ankerite crystals line the vein walls. Quartz follows center of the vein. Scale in inches. Quartz-Victoria mine dump. New Chum Line of Reef.

FIG. 26. Ankerite crustification. Typical example of a fringe or rim of ankerite lining the walls of a quartz vein. Specimen from a flatly dipping quartz spur in the footwall of a west-dipping "leg" reef near "Centre Country." Scale in inches. 820 level, Central Nell Gwynne mine.

FIG. 27. Ankerite crustification. Ankerite rims, 0.2 inch wide, coating walls of a small quartz vein, are symmetrical on both walls. Late sphalerite and galena in dark grains replaced quartz and ankerite along lower ankerite-quartz contact. Scale in inches. No. 8 level, Central Nell Gwynne mine.

FIG. 28. Ankerite crust (ank) surrounding small, angular, slate fragment (black), with later quartz (Q) surrounding and replacing ankerite. Small replacement veinlets of later quartz traverse the ankerite crust to the right of the slate inclusion. Scale: Divisions on scale are 0.1 inch. Ore Bin of Central Blue Battery, Bendigo.

FIG. 29. Spreading of wall rock. Altered quartzitic sandstone inclusions in a massive quartz body. Structure indicates that dilatancy occurred with spreading of sandstone slabs by tension and then filling and cementing of openings by quartz. Minor replacement of sandstone by quartz took place. Width of view: about 3 ft. No. 688 ft. level, Monument Hill mine.

FIG. 30. Ankerite crust coating irregular slate contact, with the ankerite band cut by replacement veinlets of later quartz. Photomicrograph. Plain light.

FIG. 31a. Typical ribbon structure as seen under the microscope with laminae of ankerite and quartz and very thin, unusually persistent, parallel layers of carbonaceous material. Specimen from a vein which followed a bedding-plane fault. Plain light. Location in Bendigo uncertain.

FIG. 31b. Same as 31a except with crossed nicols.

FIG. 32a. Photomicrograph of a part of hand specimen illustrated in Fig. 11. Curving laminae of quartz and slate form "book structure." Plain light. Ironbark mine, Sheepshead Line of Reef.

FIG. 32b. Same as Fig. 32a except with crossed nicols.

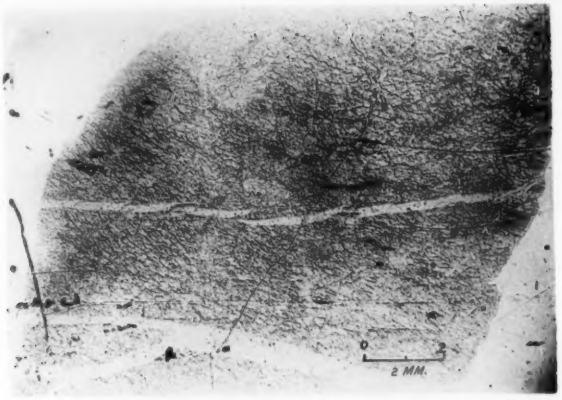

FIG. 23

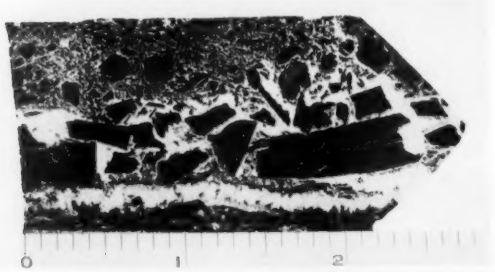

FIG. 24

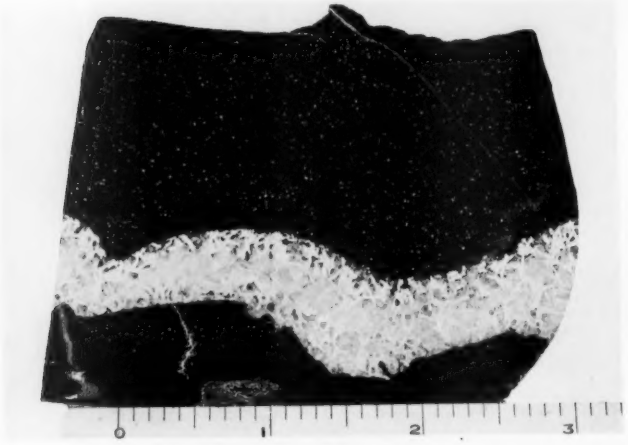

FIG. 25

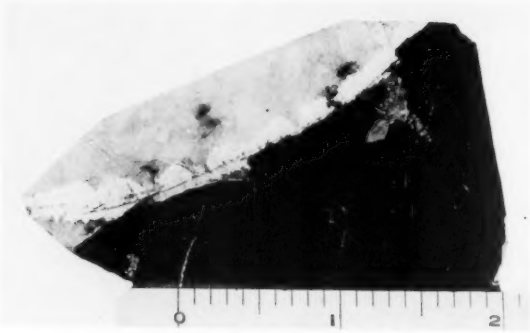

FIG. 26

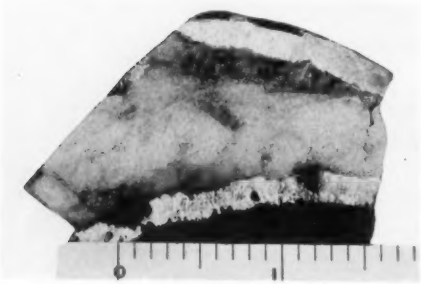

FIG. 27

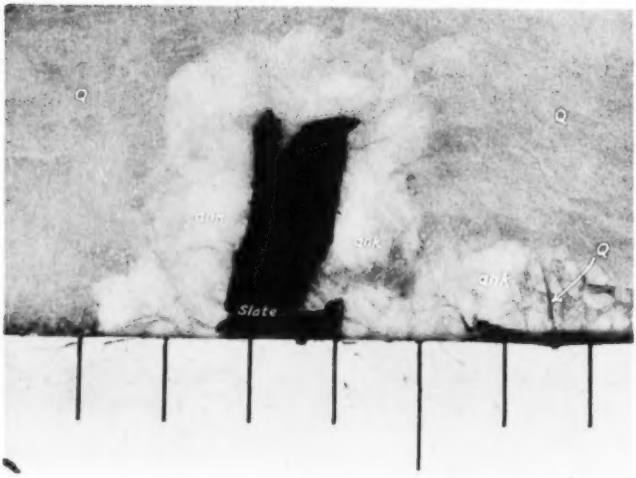

FIG. 28

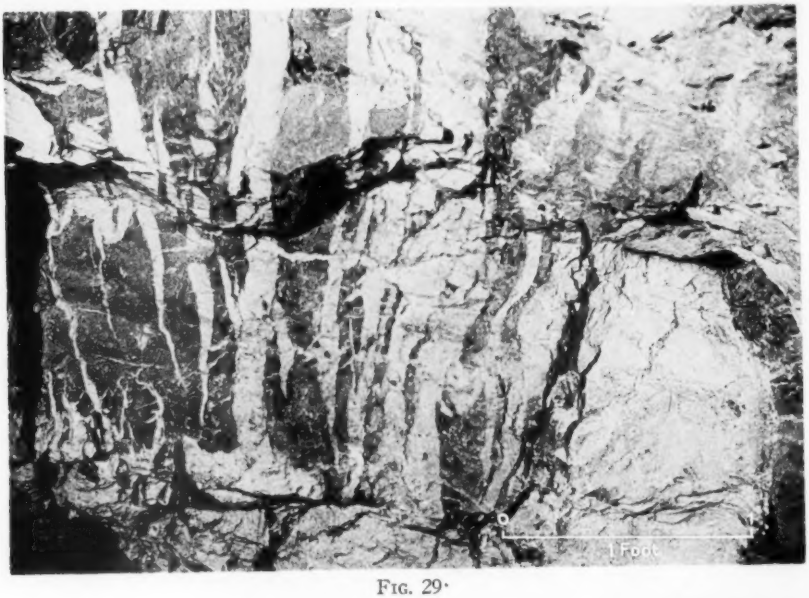

FIG. 29.

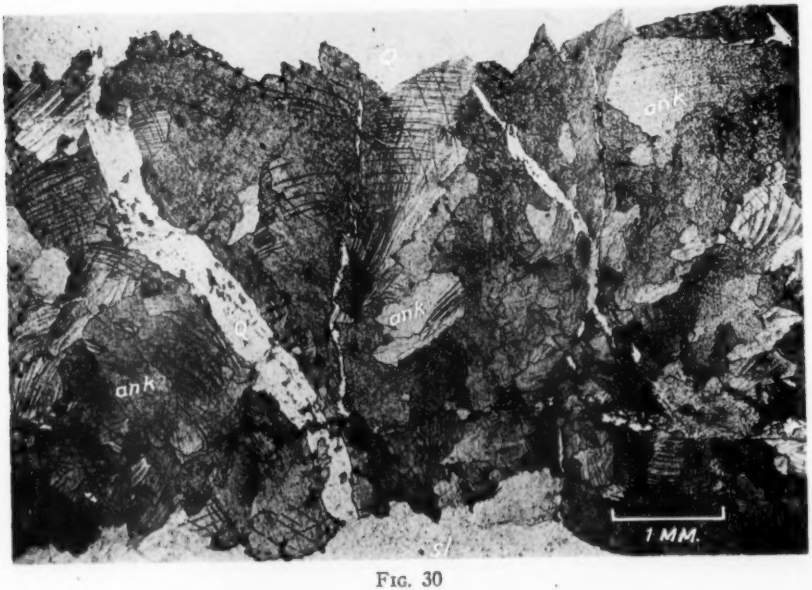

FIG. 30

FIG. 31A

FIG. 31B

FIG. 32A

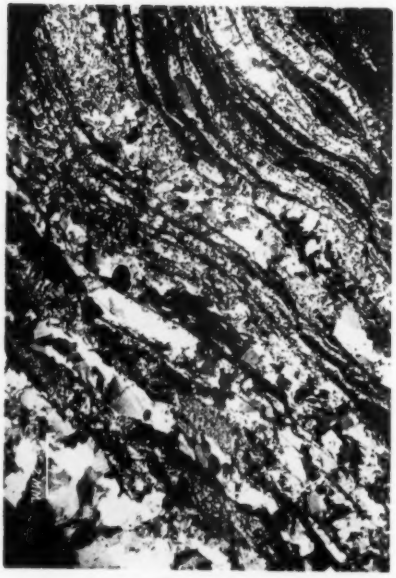

FIG. 32B

FIG. 33A

FIG. 33B

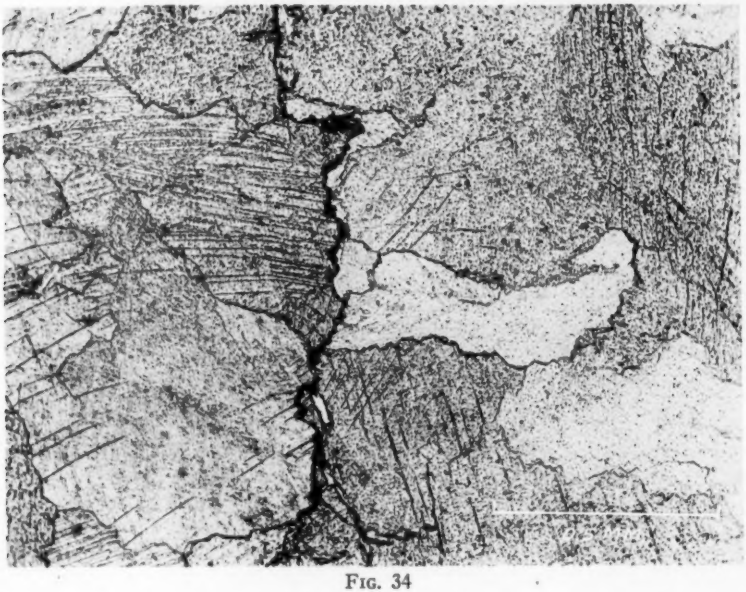

FIG. 34

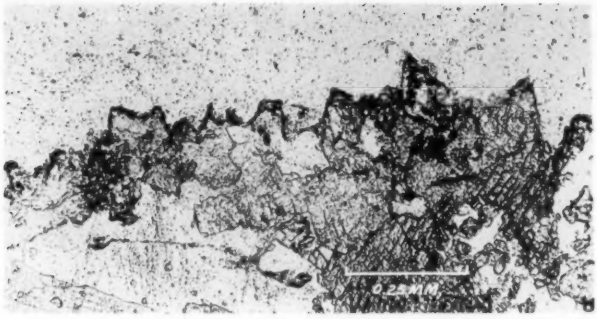

FIG. 35

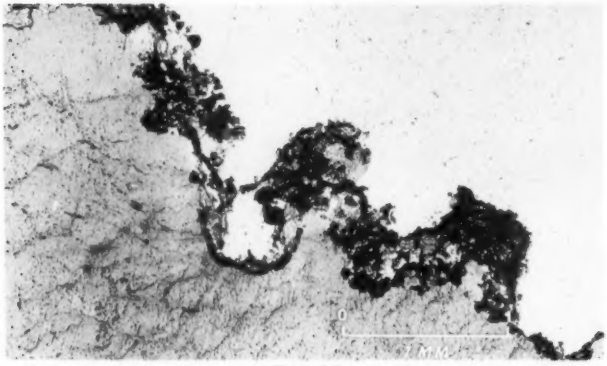

FIG. 36

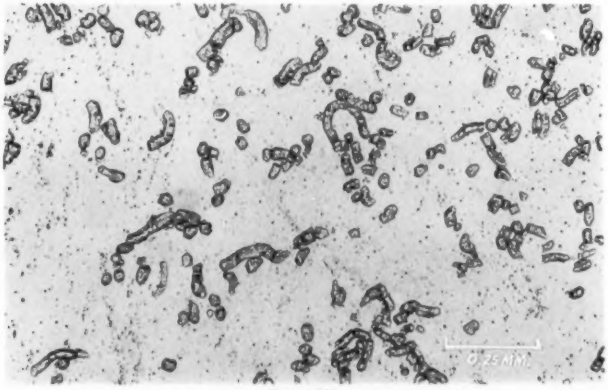

FIG. 37

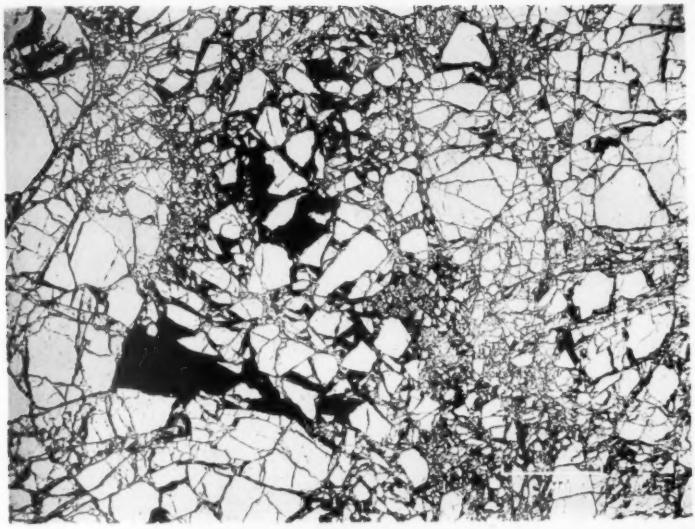

FIG. 38

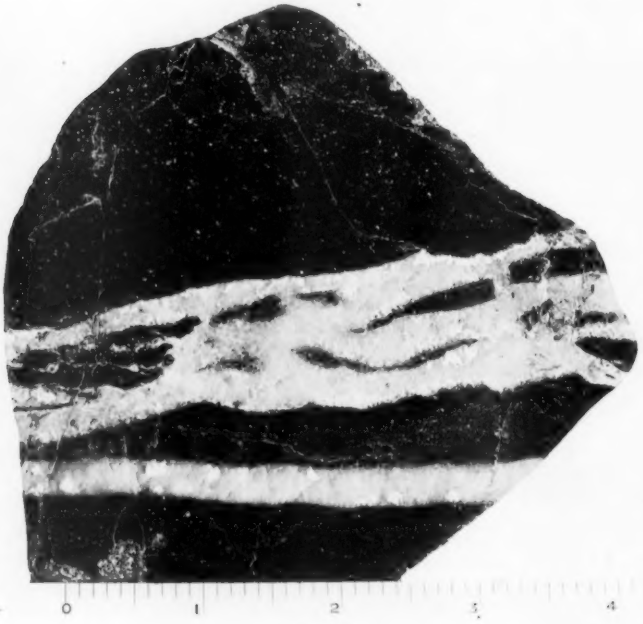

FIG. 39

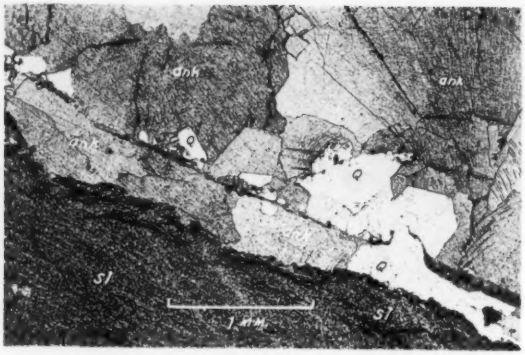

FIG. 40

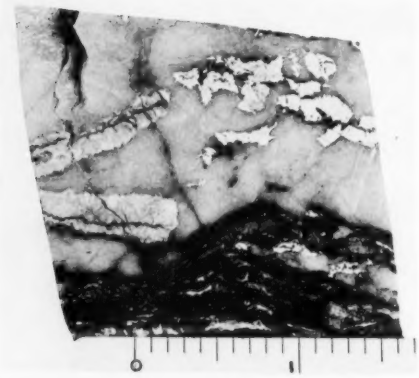

FIG. 41

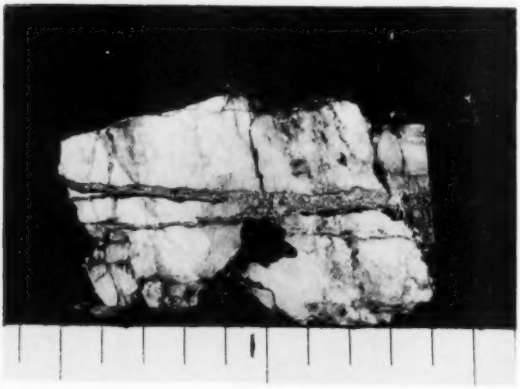

FIG. 42

ghany, California, have been called "crinkly bands" by Ferguson.[19] One of the many excellent Bendigo examples is illustrated in Figure 14. Figure 15 is an enlargement of the same hand specimen and shows in detail the minute features of the "crinkly bands."

Concerning these features in the Bendigo quartz bodies, Stone [20] observes:

> The important feature of laminated quartz is that it occurs along faults where shearing had produced sheeted rock. In part the quartz appears to have replaced this sheeted rock, and evidence for such replacement has been presented by Stillwell.[21] In other cases the quartz may have been deposited only as repeated openings made new openings. The generalization stated by McKinstry [22] that fractures formed by shear (as contrasted with tensional openings) are apt to be marked by ribbon structure is valid for Bendigo.

From these observations it is evident that book structure and ribbon structure have considerable significance in relation to the origin of the Bendigo quartz bodies and in particular places represent pre-quartz shearing, followed by replacement and deposition of quartz, intermineralization fracturing and shearing, and growth by accretion. These will be considered in more detail later.

(*4*) *Magpie quartz, chloritic quartz, and mottled quartz* (Figs. 5 and 20).—Fragments of slate and sandstone wall rock of all sizes, shapes, and arrange-

[19] Ferguson, H. G., and Gannett, R. W., Gold quartz veins of the Alleghany district, California: U. S. Geol. Survey Prof. Paper 172, pp. 38, 78–79, 1932.

[20] Stone, J. B., op. cit., p. 884.

[21] Stillwell, F. L., Replacement in the Bendigo quartz veins and its relation to gold deposition: ECON. GEOL., vol. 13, pp. 100–111, 1918.

[22] McKinstry, H. E., Use of the fracture pattern in the search for orebodies: Australian and New Zealand Assoc. Adv. Sci. Rept., Melbourne meeting, pp. 127–134, 1935.

FIG. 33a. Photomicrograph of another part of Fig. 11 and Fig. 32a. Plain light.

FIG. 33b. Same as Fig. 33a but with crossed nicols.

FIG. 34. Typical dark "crinkly band" of carbonaceous material following grain boundaries of ankerite. Plain light.

FIG. 35. Stylolitelike crinkly band following the contact between ankerite and quartz. Plain light.

FIG. 36. Typical "crinkly band" following contrasting fields of quartz. Crossed nicols.

FIG. 37. Chloritic quartz with vermicular aggregates of chlorite in a field of quartz. Plain light.

FIG. 38. Brecciated arsenopyrite (light gray) with fragments cemented by later quartz (black). Polished section.

FIG. 39. Tension fractures in quartzitic sandstone with slablike breccia fragments, later coating by ankerite (light, whitish grains), and open space filling by quartz. Specimen from a set of quartz spurs in the footwall of a west-dipping "back." Scale in inches. 688 ft. Intermediate level, Monument Hill mine.

FIG. 40. Ankerite coating slate with later quartz replacing the ankerite. Plain light.

FIG. 41. Laminated slate and quartz from a bedding-plane fault. Note the broken stublike ribbons coated by ankerite. Monument Hill mine, 688 ft. Intermediate level.

FIG. 42. Pyrite veinlets cutting across ankerite and quartz gangue. Post-quartz veins of pyrite are relatively rare. Divisions on scale are 0.1 inch. Nell Gwynne (B.M.L.) shaft.

ments are found in abundance in virtually all of the Bendigo saddle reefs, spurs, and other bodies. The abundance of breccia and its significance with respect to gold distribution has lead Bendigo miners to give local names to various types. "Magpie" quartz, for example, is a breccia made up of black slate fragments cemented by white quartz. It occurs in all stages of development, from unaltered slate fragments with sharp, angular borders to round or irregular carbonaceous patches residual from the replacement of slate by quartz.

Chloritic quartz is a fine-grained variety with a dark-green color caused by inclusions of chlorite. Typical examples are shown in Figures 19, 20, and 37. It is formed by the replacement of sandstone or slate by chlorite, followed by the encroachment of quartz on the chlorite and on the wall-rock residues. In places the chloritic quartz gives a spotted appearance to otherwise clear, milky quartz and in these places the chlorite and quartz probably are the result of replacement of slate or sandstone fragments now enclosed in the veins. Chloritic quartz is not, as a rule, associated with gold and, therefore, is looked upon with misgiving by the miners.

Mottled quartz is common in some quartz bodies and consists of dark-gray patches in colorless or whiter quartz. The darker spots are due to microscopic inclusions and, as in other varieties, probably represent residues from the brecciation and replacement of wall rock. It is usually nonauriferous.

These three varieties of quartz are the result of various vein-forming processes, including brecciation and replacement, and perhaps, in certain places, open-space filling. Their significance will be discussed in more detail later.

(5) *Brecciated quartz.*—Crushed or pulverized vein quartz with angular to rounded fragments of various sizes is found in numerous places along fault planes most of which follow the walls of older, massive, quartz bodies, but which in places cut across the larger bodies. Quartz breccias of this type are commonly uncemented. A few underground exposures, however, have been observed where the quartz breccia has been cemented and resembles the "head-cheese" breccia described by Ferguson [23] as occurring in the Alleghany district, California.

As a type of quartz, the quartz breccia is relatively rare, but as an indicator of vein-forming processes it has considerable significance. The brecciation was undoubtedly caused by recurring movements on some of the pre-mineral faults and as such is indicative of intermineralization or post-mineral fracturing. Late quartz cementing brecciated quartz fragments is good evidence of more than one generation of vein quartz.

(6) *Sheared quartz.*—As noted by Stone [24] ". . . quartz is commonly sheeted, polished, or even crushed by later movements." The sheeting and shear planes in quartz are usually approximately parallel to the pre-quartz fault walls that bound the quartz bodies (Fig. 21). In places the sheets are more or less regularly spaced across the full width of a vein; in other places they may be concentrated along one wall or another. Rarely does the post-

[23] Ferguson, H. G., and Gannett, R. W., Gold quartz veins of the Alleghany district, California: U. S. Geol. Survey Prof. Paper 172, p. 48, 1932.

[24] Stone, J. B., op. cit., p. 884.

quartz sheeting or shearing resemble the laminated quartz, although possibly some of the ribbon structure was caused by post-quartz sheeting or shearing.

Evidence of post-quartz shearing is abundant in thin section. Lines of finely granular quartz, with roughly parallel orientation, or contained within larger quartz grains having marked strain polarization, are common. Mortar structure, strain figures, microbreccia, and granulation zones are present in many of the thin sections, and provide further evidence of intermineralization and post-quartz shearing.

(7) *Phantom veinlets.*—Tiny veinlets of water-clear, colorless quartz, ranging from 1/40th to 1/10th of an inch wide, are rather common, cutting the massive white quartz of the district. The clear quartz cements small fractures in the massive quartz; but in places the fractures are not completely filled and occur as open gashes with the walls coated by small flat crystals of the water-clear quartz. These veins are similar in all respects to the "phantom veinlets," common in the California gold-quartz veins described by Adams,[25] Hulin,[26] Johnston,[27] and others.

Two types of phantom veinlets occur at Bendigo. One is made up of a series of short, gash-shaped veinlets that fill tension openings. These are illustrated in Figures 21, 22, and 23. The other occurs in wide quartz veins and follows sheetlike breaks which tend to parallel the strike fault along which the quartz body occurs. This is considerably more persistent than the first and is illustrated in Figure 21.

Under the microscope the phantom veinlets appear as clear, sharp quartz cutting across the earlier turbid quartz .(Fig. 23). With crossed nicols the veinlets are not as conspicuous as under parallel light and prove to be made up of grains usually with the same optical orientation as the older quartz. This characteristic led Adams [28] to observe that "the introduced material has been deposited in perfect orientation with each fractured crystal which it cements."

Considerable significance is attached to the occurrence of phantom veinlets. The presence of two sets of veinlets cutting earlier, massive quartz indicates that intermineralization fracturing took place during vein formation and that more than one generation of quartz was deposited, although quartz of the late stage occupies much less space than the earlier variety. Furthermore, it is not uncommon to find native gold localized along the "phantom veinlets," indicating that intermineralization fracturing tended to maintain permeability in the veins, and that some of the gold at least followed this stage of fracturing and was accompanied by quartz of the water-clear variety.

ORIGIN OF THE QUARTZ BODIES.

Direct information on the origin of the Bendigo quartz bodies can be obtained from a detailed study of the varieties of quartz present, the ore textures,

[25] Adams, S. F., A microscopic study of vein quartz: ECON. GEOL., vol. 15, pp. 623–664, 1920.
[26] Hulin, C. D., Structural control of ore deposition: ECON. GEOL., vol. 24, pp. 15–49, 1929.
[27] Johnston, W. D., Jr., The gold quartz veins of Grass Valley, California: U. S. Geol. Survey Prof. Paper 194, 1940.
[28] Op. cit., p. 632.

both megascopic and microscopic, and the structural relations of the individual quartz bodies. Ample evidence indicates that (1) open-space filling, (2) replacement, and (3) growth by accretion were active in the formation of the sadle reefs, spurs, and related bodies. Observations indicative of the operation of these processes are summarized in the following paragraphs.

(1) *Evidence of Open-Space Filling.*

(*a*) *Vug, druse, and comb texture.*—Actual openings exist as vugs in many of the Bendigo quartz bodies, particularly in the massive quartz which makes up the center or heart of the saddle reefs. Most of these vugs are lined with projecting quartz crystals (Fig. 9). The presence of vug, druse, and comb texture in the structural environment provided locally at Bendigo is evidence *par excellence* of open-space filling during mineral deposition.

(*b*) *Breccia texture.*—Brecciated fragments of slate and sandstone, as well as sulfide minerals such as arsenopyrite and pyrite, are abundant in most of the quartz bodies. In many places it can be shown convincingly that the wall-rock breccia was the product of replacement; but in other places, where the fragments show distinct rotation, or where they can be fitted together with matching edges, deposition of the cementing quartz or ankerite in open-spaces is demonstrated. Some of the veins have angular, slablike inclusions characteristic of "domino" breccia (Figs. 24 and 39). Open-space filling, therefore, is proved regardless of the mechanism by which the breccia and openings were formed.

(*c*) *Crustification.*—Crusts of ankerite, remarkably uniform in thickness, coat the walls of many spurs, surround angular breccia fragments within massive quartz, and line the walls of many saddle reefs and spurs (Figs. 26 and 27). Where it coats both walls of a spur, the ankerite is symmetrical and has a uniform width throughout the extent of the spur; in other spurs the crust may be absent or, if present, unsymmetrical. The crusts are more abundant in the small branching veinlets adjacent to larger spurs or saddle reefs. Here the thickness of the ankerite crust is approximately uniform regardless of the width of the spur, saddle reef, or vein. Although relatively rare compared with the amount found in spurs and saddle reefs, ankerite crusts are found in places in the "backs" and leg reefs. It is particularly prominent where book structure is well developed, with the ankerite coating the walls of slate laminae or leaves (Fig. 12).

Lindgren [29] impressed with the significance of the ankerite crusts he observed in the Bendigo mines, described and illustrated a fairly typical specimen, concerning which he concluded as follows:

[29] Lindgren, W., Vein filling at Bendigo, Victoria: ECON. GEOL., vol. 15, no. 4, pp. 312–314, 1920.

FIG. 43. Native gold (light) replacing quartz (dark). Polished section. 688 ft. Intermediate level, Monument Hill mine.

FIG. 44. Native gold (light) replacing quartz and ankerite (dark). Polished sections. Nell Gwynne (B.M.L.) shaft.

FIG. 43

FIG. 44

It seems difficult to explain these relations by any other theory than that the cavity in the slate was first formed and that it remained open until the coating of ankerite had been deposited. At that time the character of the solutions changed and quartz was deposited . . . my main proposition is that the cavity was there before the quartz was deposited.

It has been suggested that the ankerite is in reality a replacement product and that the crusts, therefore, do not indicate open-space deposition. According to this idea, the contact between the slate or sandstone wall and the vein quartz is a permeable zone along which carbonate-bearing solutions replaced the wall rock and quartz. Opposed to this idea, however, is ample evidence that the quartz is later than the ankerite. The contact between ankerite and quartz is usually a sinuous line, but close examination shows that in many places quartz replaces ankerite and that ankerite is traversed by a network of tiny quartz veinlets (Figs. 28, 30 and 40). As Lindgren [30] remarked, ". . . a thin section demonstrates at once that the quartz is later than the ankerite, replacing it along the contact and along the numerous veinlets." Moreover, where ankerite crusts are well developed, there is no indication that ankerite replaces wall rock; rather it appears to coat the rock walls, with the original irregularities and sinuosities preserved by the ankerite crusts.

(*d*) *Spread wall-rock structures.*—In many places "matching walls" of quartz veins and parallel rock slabs and slivers in the veins would fit together moderately well if the quartz filling were removed (Fig. 25). These are taken to indicate that open-space filling of "dilatant partings," to employ an expression used by Farmin,[31] has taken place. Spreading of wall rocks followed by quartz filling is expressed in several ways.

Slabs and slivers of country rock, particularly quartzitic sandstone, are common in certain saddle and spur reefs (Fig. 29). Although their sides are somewhat modified by attrition and by replacement, it is apparent in many places that the slabs would fit together fairly well if the quartz were removed. Moreover, "flexed straps," both broken and unbroken, similar to those described by Farmin [32] in the Grass Valley district, California, are found in places associated with "spread" structures. The supposition here is that if the quartz were removed the rock slabs could be reassembled much as an accordion is collapsed, into a single rock body of smaller volume. Filling of the spread structures is confirmed in places by ankerite crusts around the rock slabs and by occasional vugs in the quartz.

Wedge-shaped spurs "making off" from the footwall of bedding-plane faults on the limb of a fold below the arch of the anticline are rather common (Fig. 7). In many of these opposite walls of the spurs match fairly well, and the quartz was deposited in an open space. Additional evidence of open-space filling is found where ankerite crustification coats the spur walls.

As noted by Stone,[33] many spurs of this type show "entire absence of replacement," for there is a sharp boundary between slate or sandstone and

[30] Lindgren, W., Idem, p. 313.

[31] Farmin, Rollin, Host rock inflation by veins and dikes: ECON. GEOL., vol. 36, pp. 143–174, 1941.

[32] Farmin, Rollin, op. cit.

[33] Stone, J. B., op. cit., fig. 8, p. 887.

quartz. Sharp boundaries, of course, are not necessarily proof of lack of replacement. In places, metasomatism has played some part in the emplacement of the quartz. Figure 3a, for example, illustrates the conflicting testimony found in some of the spurs. Here a nearly horizontal quartz spur cuts across steeply dipping sandstone and slate beds. Not only do the opposite walls fail to match, but also the bedding planes on opposite sides of the spur form a continuous line, rather than being offset at right angles to the vein walls. Moreover, if the quartz were removed and the walls pushed together, the beds would be decidedly offset. Probably these departures from the normal spread structures are more apparent than real and are due to the fact that the exposed section is not at right angles to the strike or dip of the spur. The direction of movement of the vein walls was not parallel to the plane of the exposed section. Considerable rotation accompanied by distortion of the wall rocks probably took place during spreading. In addition, replacement of wall rock by quartz somewhat modified and obscured the true relations.

Spreading of wall-rock structures followed by open-space filling of quartz has been detected in a few places where changes in strike or dip occur in a fault reef, a leg reef, or an irregular vein. Here openings have been created by the movement of irregular fault walls parallel to the strike of the vein.[34] In these relatively few examples in Bendigo, open-space filling is indicated by "matching walls," an angular "domino" breccia in the vein, and vug and comb texture in the quartz.

There is little or no evidence that lunate cavities of the type suggested by Dunn [35] formed as a result of the bending or arching of strata during rock folding, and less evidence that filling of such cavities was an essential part of the formation of the saddle reefs. As first suggested by McKinstry on the basis of his observations during 1933 and 1934, however, there is considerable evidence that open cavities formed as a result of the reverse faulting superimposed upon the folded rock.[36] The triangular shape of many of the saddle reefs, localized at the crest of the anticlines beneath conjugate thrust faults, suggests that the quartz occupies openings that formed as a result of the faulting. The nature of the displacement on the faults, plus a theoretical analysis of the cause and nature of faulting, suggests that the triangular-shaped openings were created by the dragging apart of beds at the crests of the folds during faulting. These openings were subsequently filled by quartz.

It should be emphasized that the shape of the saddle reefs themselves, with triangular cross section and curving bottoms limited by the arch of bedding, suggests open-space filling (Figs. 1 and 4). From the profusion of angular to rounded inclusions of wall rock in the quartz, it is inferred that these openings did not have extensive unsupported walls, but that a triangular rubble-filled cavity, with considerable extent parallel to the axes of the anticlines, formed as a result of the faulting. The rubble gave considerable support to the fault walls and was partly or completely replaced by quartz (Fig. 5).

[34] Newhouse, W. H., Openings due to movement along a curved or irregular fault plane: Econ. Geol., vol. 35, pp. 445–464, 1940.

[35] Dunn, E. J., Report on the Bendigo gold field (No. 1): Victoria Dept. of Mines, 1896.

[36] McKinstry, H. E., Use of the fracture pattern in the search for orebodies: Australian and New Zealand Assoc. Adv. Sci. Rept. of the 52d Meeting, Jan. 1935, p. 132.

Open-space filling of such a cavity is further suggested by the numerous druse-lined vugs in the massive quartz and by ankerite crusts surrounding many of the unreplaced wall-rock fragments.

Concerning the relative importance of open-space filling, Stillwell[37] commented:

> The extent to which fissure filling has occurred will always be more or less uncertain. It is difficult to picture cavities of any size, even 1 foot wide, at great depths below the surface, and one has to remember that the Bendigo quartz veins were buried beneath the surface at the time of their formation at very much greater depths than they are now. Yet in some reefs, e.g., the centre reef at 810 feet in the Ironbark, there are large and numerous vugs some of which are 2 feet or more in diameter; and when such vugs, averaging perhaps 1 foot wide, appear by the score in a single reef, it must be taken as evidence that cavities can exist at great depth.

(2) *Evidence of Replacement.*

Opinions on the amount of replacement in the Bendigo quartz bodies differ considerably. Although Dunn,[38] Taber,[39] Lindgren,[40] and Stone [41] recognized evidence of replacement locally, apparently they thought it relatively unimportant. Stillwell,[42] on the other hand, was the first to recognize and emphasize the fact that replacement played an important part in the formation of the saddle reefs, "backs," and laminated structures. He presented strong evidence to support his views. Some of his observations, together with other convincing evidence of replacement, are summarized in the following paragraphs.

Proof of the part played by metasomatism in the formation of the Bendigo quartz bodies is based on the fundamental principle that ". . . recognition of replacement depends most commonly on the recognition of a host structure in spite of varying degrees of modification by later guest minerals." [43] Application of this principle involves recognizing and tracing an original structural continuity of the host rocks or minerals through later quartz bodies. This can be done in a variety of ways in the Bendigo quartz bodies, particularly where (a) transected structure and textures are present, and (b) where selective replacement of favorable slate beds occurred.

(*a*) *Selective replacement* of particular beds in the folded slates and quartzites is very common. Figure 8, for example, illustrates selective replacement by quartz of a drag-folded slate bed. Continuity of the original slate bed is proved in examples of this type by the abundance of oriented slate inclusions in the quartz and by the drag folds which can be traced down the

[37] Stillwell, F. L., The factors influencing gold deposition in the Bendigo goldfield: Commonwealth of Australia Advisory Council of Science and Industry Bull. 8, Part II, page 34, 1918.

[38] Dunn, E. J., Reports on the Bendigo goldfield (Nos. I and II): Victoria Dept. of Mines, 1896.

[39] Taber, S., Origin of the Bendigo quartz veins: Econ. Geol., vol. 13, pp. 538–546, 1918.

[40] Lindgren, W., Vein filling at Bendigo, Victoria: Econ. Geol., vol. 15, pp. 312–314, 1920.

[41] Stone, J. B., The structural environment of the Bendigo goldfield: Econ. Geol., vol. 32, pp. 867–895, 1937.

[42] Stillwell, F. L., Replacement in the Bendigo quartz veins and its relation to gold deposition: Econ. Geol., vol. 13, pp. 100–111, 1918.

[43] Bastin, E. S., and others, Criteria of age relations of minerals with especial reference to polished sections of ores: Econ. Geol., vol. 26, no. 6, pp. 561–610, 1931.

limbs of the anticline to the place where quartz gives way to unreplaced slate. Selective replacement of the slate is indicated by the sharp contacts of quartz with the quartzitic sandstone on both the top and bottom of the drag folded slate.

Symmetrical "inner reefs" are rather common and, like the replaced drag folds, formed by selective replacement of slate beds at the crest of anticlines. Excellent examples are shown in Figure 1. Here quartz has replaced two thin slate beds separated by 1 to 2 feet of quartzitic sandstone at the crest of the Deborah anticline below the main saddle reef above the 739-foot level. Inner reefs of this type more nearly approach the lunate shape of the classic saddle reef than do the other quartz bodies; but their origin by selective replacement, rather than by open-space filling, is evident from the abundance of oriented slate residues in the quartz and from the complete lack of evidence of spreading apart of the beds during folding. Thickening of the beds on the crest of the folds and thinning on the limbs is obvious, but this was accomplished by rock flowage rather than by spreading apart of beds. Druse-lined vugs, comb texture, crustification, and other textures indicative of open-space filling are completely lacking.

(*b*) *Irregular spurlike quartz bodies*, such as that illustrated in Figure 3b, are difficult to explain by any other mechanism than replacement. Their irregular outlines with no semblance of matching walls, their structural relations, in places with continuity of bedding across the quartz bodies, and their size and position preclude the possibility of open-space filling.

An excellent example of this type of spur has been described and illustrated by Stillwell.[44] This is a gold-bearing spur with an arched shape that resembles a saddle reef, but it is not localized at the crest of a fold and it crosscuts slate bedding planes. The spur is 1 to 2 feet thick, has irregular, nonmatching walls, and is made up of mottled quartz with many oriented slate inclusions. These inclusions are generally angular in outline and have not been moved or rotated from their original position in the slate bed crosscut by the spur; undisturbed slate bedding is preserved in them and can be traced from fragment to fragment. All stages in the replacement process are detectable, from unreplaced, black slate to carbonaceous residues and ghostlike outlines of the original fragments. So well preserved are the angular fragments and so clear is the evidence of replacement origin that Bateman[45] cited this occurrence as an example of unsupported, angular inclusions of rock, now surrounded by vein matter, that resulted from the operation of the replacement process.

Another somewhat different example of an irregular spur that formed by replacement is illustrated in Figure 3b. This quartz spur is localized in sandstone at the crest of an anticline immediately above a sandstone-slate bedding-plane boundary. The extremely irregular outlines of the spur and the nature and distribution of the inclusions in the quartz suggest that the spur formed by replacement of the sandstone. This suggestion is verified by the transect-

[44] Stillwell, F. L., Vein filling at Bendigo, Victoria: Econ. Geol., vol. 16, pp. 153–159, 1921.
[45] Bateman, Alan M., Angular inclusions and replacement deposits: Econ. Geol., vol. 19, pp. 504–520, 1924.

ing relations shown where the lower part of the spur extends across the sandstone-slate boundary into the slate. Obviously, this boundary extended uninterruptedly across the area now occupied by quartz.

The localization of certain spurs, as well as some of the other quartz bodies (such as those formed by selective replacement of folded slate), probably is explained by the principle of dilatancy.[46] A granular mass, such as the sandstone bed, probably expands in volume with change in shape during folding (or in places because of later superimposed faulting) in such a way that a local increase in porosity takes place between the sand or slate grains at the crest of the folds. Such an increase in porosity was probably accompanied by an increase in permeability in a restricted zone along the axes of the folds. The permeable, intergranular pores provided space for the flow of ore solutions, as well as a locus for the replacement of the rock components by quartz.[47]

In examples such as the one illustrated by Stillwell, the change in shape accompanied by change in volume was probably expressed by minute fracturing of the bed rather than by an increase in intergranular space. The minute, interlacing fractures provided a permeable zone and loci for attack on wall rock by silica-bearing solutions; this resulted in the cementation of angular slate fragments by quartz.

(*c*) *Laminated quartz.*—That book structure, ribbon structure, and crinkly banding are related and gradational phenomena, and that they have a common origin is clearly demonstrated at Bendigo. Moreover, it is clear that most of these structures resulted from the deposition of quartz, ankerite, or sulfide minerals, along bedding-plane faults where the wall rock had been previously sheared. The leaves and ribbons are thin slabs or slivers of country rock, bedding or foliation planes, original slickensides from the shear zones, or residues of wall rock that have escaped replacement. The crinkly bands are stylolitelike residues of carbonaceous material left over from the replacement of slate or residues rejected from crystallizing quartz.

In addition to origin by replacement, local evidence of open-space filling is present where apparently dilatant partings developed in foliated wall rock followed by deposition of quartz and ankerite in parallel bands. This also resulted in a type of book structure and ribbon structure, and where accompanied by replacement may not be distinguishable from the same structures caused by replacement alone. Post-quartz shearing also produced laminated structure but in most places probably formed along previously existing leaves or ribbons and simply resulted in post-quartz shearing of already laminated veins.

[46] Mead, W. J., The geologic role of dilatancy: Jour. Geology, vol. 33, pp. 685–698, 1925.

[47] In a recent paper on Homestake geology, Noble, Harder, and Slaughter suggested what appears to be a new and somewhat different application of the concept of dilatation to ore deposits. According to Noble and his co-authors, "expansion or inflation of the rock in a zone of cross folding" in the district resulted from "a reorientation of minerals" in the crenulated zones. Noble showed that "the crenulations in a schist are discontinuous faults of microscopic size and that the well-oriented minerals lose their orientation in the crenulated zones. Since no new minerals are formed, but merely the old minerals are thrown out of orientation by bending, fracturing, and rotation in the crenulated zones, the conclusion seems inescapable that, as a result of the development of crenulations, the rock has increased in volume." The consequent dilatation in the zone of cross folding probably had a profound influence on the localization of the Homestake ore bodies. See: Noble, J. A., Harder, J. O., and Slaughter, A. L., Structure of a part of the Northern Black Hills and the Homestake mine, Lead, South Dakota: Geol. Soc. America Bull., vol. 60, pp. 321–352, Feb. 1949.

These conclusions, in general, agree with those of McKinstry and Ohle [48] who reviewed in considerable detail the controversial origin of laminated structures in gold-quartz veins. No attempt will be made here to repeat the arguments, pro and con, regarding the origin of ribbon structure and book structure. Only those factors bearing on the Bendigo occurrences will be discussed. These factors may be considered under the following topics: (1) pre-quartz shearing; (2) replacement of sheared country rock by quartz, etc.; (3) origin of laminated structure by dilation; (4) evidence against other processes such as accretion, force of growing crystals, etc.

Pre-quartz shearing. The individual leaves, ribbons, or laminae, where recognizable as remnants of wall-rock material, invariably have polished or slickensided surfaces. These surfaces occur in varying degrees of development from slightly grooved or polished surfaces to "graphitic slips" that are composed of highly polished, black, carbonaceous slate which cleaves in curving plates. In most places these products of shearing are preserved as "fossil slickensides" by later quartz that fills the grooves and molds around the minute ridges and that tightly adjoins the polished surfaces with no suggestion of polishing or granulation of the quartz.

The pre-quartz shear planes developed parallel to bedding and were commonly localized in slate beneath a massive quartzitic sandstone bed or in a thin slate bed enclosed in massive sandstone beds. They probably originated as bedding-plane slips during folding and served to localize both the major and minor faults that were superimposed on the anticlines sometime subsequent to folding.

That the shearing along the ribbons and leaves was pre-quartz is proved by the fact that many of them are crosscut by later veinlets of quartz, which, in places, slightly offset the laminae. In most places, however, the laminae continue in a straight line across the quartz gap with no indication of fracturing or shearing in the intervening quartz. Figure 18 is an excellent illustration of this feature. A group of quartz veinlets in ladder structure cuts across sheared slate and ankerite ribbons without offsetting these laminae. That the slate ribbons have been sheared and polished is proved by polished and grooved surfaces on the sides of the specimen.

Sheared slate laminae intersected by later quartz are illustrated in Figures 12, 14, and 16. Of interest in these specimens is the fact that the massive, milky gray quartz extends from one side of the laminae through gaps in the slate laminae to the other side with identical color and texture on both sides and with no suggestion, megascopically or microscopically, that shearing along the laminae extends across the quartz. The only conclusion possible is that the shear planes along the leaves and ribbons are pre-quartz.

Additional conclusive evidence that the shearing was pre-quartz is illustrated in Figure 14 and in Figure 15, which is an enlargement of a selected part of the former. Arsenopyrite crystals, 1/10 of an inch or more across, transect a stylolitelike crinkly band of sheared carbonaceous material with identical quartz adjoining the band on both sides. Inasmuch as arsenopyrite is older than quartz, the arsenopyrite must have been deposited by replacement of

[48] McKinstry, H. E., and Ohle, E. L., Jr., op. cit.

sheared slate before the quartz was introduced. Later selective replacement of foliated slate by quartz preserved the shear planes, produced the crinkly band, and left the arsenopyrite unaffected. Had the shearing been post-quartz, the arsenopyrite would have been fractured and probably offset.

In examples such as that illustrated in Figure 12 where crustification of sheared slate leaves by ankerite has occurred, obviously the coated walls must have been pre-ankerite and pre-quartz.

Replacement of sheared country rock by quartz. Direct evidence of replacement of foliated slate bedding planes, shear planes, and graphitic slips is found by close examination of individual laminae. Encroachment of quartz or ankerite on the sides of laminae is obvious in many places. In Figure 14, for example, characteristic embayments of quartz into slate are prominent along the slate-quartz contact. Moreover, a network of tiny quartz veinlets, not readily visible to the unaided eye or in the photograph, ramifies through the slate wall rock beyond the prominent slate-quartz contact. These veinlets are interpreted as manifestations of an advanced stage of the replacement process. Where embayments into slate bands are pronounced, the resulting laminae have a wavy and tortuous course. In other places where replacement proceeds more or less parallel to an original straight surface, the laminae too are relatively straight and parallel.

Locally, replacement of foliated country rock by quartz was a two-stage process. First, ankerite replaced foliated slate, as is illustrated in Figure 18, and second, quartz replaced the carbonate mineral (Figs. 28, 30, 31). The laminae between the quartz bands, then, are foliated slate and ankerite; foliated slate, ankerite, and quartz; or foliated slate and quartz. In other places arsenopyrite or pyrite clearly has replaced slate bands, forming individual laminae of sulfides (Fig. 14).

The gradational nature of the leaves, ribbons, and crinkly bands, both along the strike of the veins and from the vein walls toward the center of the veins, is one of the clearest evidences of replacement. This is shown in hand specimens such as those illustrated in Figures 12 and 16. Near the walls the leaves are clearly defined, foliated slate which forms book structure. The width of the leaves is probably determined by the spacing of the pre-quartz shears. Farther away from the walls the slate leaves become narrower, and the quartz bands increase in width until the leaves are no longer clearly recognizable as slate, but are slaty residues, carbonaceous material, chlorite or sericite, and are then more accurately designated as ribbons. In this stage, the opposing walls of the laminae fail to match in most places, and in many places a decided waviness, tending toward crenulation, appears in the laminae. The ribbons are wider apart than the leaves in book structure, tend to become discontinuous lines of dots and dashes, and are undoubtedly residues in various stages of digestion of replaced wall rock; individual ribbons are traced across bridges of quartz by faint, dark coloration in the quartz; frayed-out ends occur; and quartz forms around the ribbons and appears to be of the same age, texture, and color on both sides of individual laminae. Usually no indication of successive deposition is present.

The process can be traced microscopically, as well as megascopically, although with less ease and clarity, because in an underground exposure or in a hand specimen considerable surface area can be viewed at once whereas under the microscope several thin sections must be compared and the observations pieced together to see the whole picture. Microscopic book structure from a part of the specimen illustrated in Figure 11 is shown in Figures 32 and 33. The wider dark bands, in part curving, are slate. Some of these grade laterally into narrow black bands that, if isolated, would be called ribbons. Other narrow bands parallel to the slate leaves ordinarily, if alone, also would be called ribbons. Therefore, in a single specimen and even in a single thin-section leaves and ribbons occur together. Both show replacement by quartz.

As the replacement process advanced, the ribbons became appreciably thinner, and in places, where they became sinuous and irregular, they graded into typical crinkly bands. Figure 14 shows such a gradation in one of the prominent bands in the center of the specimen; elsewhere in the same specimen typical crinkly bands are well developed. It is significant that not only do leaves and ribbons occur in the same place in the vein and in the same hand specimen, but also that in places they grade directly into crinkly bands.

Microscopic examination shows that the crinkly bands, except for their extreme irregularity, resemble typical ribbons in composition and texture. They consist of dark carbonaceous material that follows the grain boundaries of quartz or ankerite (Figs. 34, 35, 36). In fact the irregularities and sinuosities of the carbonaceous bands may be traced directly to their habit of following with precision the outline of curving boundaries of individual mineral grains. In Figure 34, for example, the dark carbonaceous material does not cut across the ankerite grains, but rather follows the boundaries of interlocking grains so that a sinuous line is formed. Similar features are shown in Figures 35 and 36. In the former the jagged, sawlike carbonaceous band is a direct reflection of the sharp angular outlines of the ankerite crystals as they interfinger with quartz grains. In Figure 36 the curving band is due to irregularities in grain outlines along the contact of contrasting fields of quartz.

The position of the carbonaceous material around individual grain boundaries suggests that it is a residue rejected from crystallizing ankerite or quartz. The growing crystals apparently reject solid particles of carbonaceous material either by diffusion or by mechanical pushing aside rather than incorporating the material as inclusions in the new crystals, or by complete removal in solution. Stillwell [49] suggested that this mechanism is the final stage of the replacement process and accounted for the origin of laminated structure in this way. After all the slate constituents had been removed by replacement an insoluble, opaque residue of carbonaceous material remained. This was displaced by the growing crystals to the margins of the grains where dark laminae were formed.

The laminae were straight in most places, but where influenced by curving grain boundaries sinuous or stylolitelike bands developed.

[49] For details see Stillwell, F. L., Factors influencing the gold deposition in the Bendigo gold field: Australian and New Zealand Assoc. Adv. Council Sci. and Ind. Bull. 4, pp. 33, 34; Bull. 8, p. 33, 1918.

The crinkly bands in the Bendigo quartz bodies closely resemble similar structures in the veins at Alleghany, California, that were first described by Ferguson. Ferguson [50] suggested that those at Alleghany were due to folding of ribbons for he observed that:

> . . . where there was opportunity for detailed study of the relations of quartz showing crinkly banding to the straight ribbon quartz and to the structure of the vein it was found that the crinkly banding occurs in such relations to the minor thrusts, particularly in the wedges of quartz between two such thrusts, as to suggest that the crenulations represent deformation in the quartz after crystallization.[51]

Although it is likely that the major sinuosities in the crenulated ribbons at Alleghany are due to distortion of bedding or foliated rocks (pre-quartz drag folding), it is more probable that the crinkly bands themselves (the stylolite-like ribbons) were caused by replacement of foliated rock rather than by deformation in the quartz after crystallization. If replacement is accepted as the origin of the crinkly bands, then their position in wedges at the intersection of faults, such as is illustrated by Ferguson, would seem to be due to the activity of ore solutions along the permeable zone created by the intersection of faults. Away from the intersections along the quartz veins where the crinkly bands grade into normal, straight ribbons, the solutions were probably less active and replacement less intense.

The extreme irregularity of many of the crinkly bands, as well as their microscopic characteristics, precludes the possibility that the ribbons were due to post-quartz shearing or to intermineralization shearing. If recrystallization of quartz has taken place, as is postulated by some writers, then the crinkly bands could have formed by differential solution and compaction in the same way as stylolites in limestone are believed to originate. However, no evidence of recrystallization has been found. The effect of recrystallization would be to destroy all original textures and structures in the veins, so that those features observed at the present time would have no significance as far as original mineral deposition is concerned and would have no value in the study of mineral sequence or genesis. Such is not believed to be the case.

From the megascopic and textural relations and from the evidence in thin sections, the conclusion seems justified that the laminated structures in the Bendigo quartz bodies originated by retention of original, pre-quartz bedding planes, shear planes, and foliate structures through replacement of slate wall rock by quartz, ankerite, and other minerals.

Origin of laminated structures by dilatancy. Concerning the origin of quartz veins at Grass Valley, Calif., Farmin [52] concluded that ". . . vein deposition through inflation of partings in the country rock by an injected, quasi-magmatic fluid is the mechanism which best explains the occurrence." From the context of his paper, it appears that Farmin included the origin of book structure and ribbon structure in this conclusion. McKinstry and Ohle [53]

[50] Ferguson, H. G., and Gannett, R. W., Gold quartz veins of the Alleghany district, California: U. S. Geol. Survey Prof. Paper 172, p. 79, 1932.

[51] Ferguson, H. G., and Gannett, R. W., Idem, p. 78.

[52] Farmin, Rollin, Host rock inflation by veins and dikes at Grass Valley, California: Econ. Geol., vol. 36, pp. 143–174, 1941.

[53] McKinstry, H. E., and Ohle, E. L., op. cit.

object with good reason to "inflation of rock structures by invading solutions . . . because it calls for solutions having the nature of 'ore magmas,' " and because such solutions are chemically improbable. Other objections to the mehanism could be cited—among them, the fallacy of basing such a conclusion on the analogy of quartz veins to igneous dikes. Although many gross structural resemblances can be pointed out, in detail there are many differing field relations. Moreover, to pursue the analogy is to overlook or misinterpret the evidence for replacement, mineral sequence, and ore and rock textures. No recognition is given to the significance of fracture patterns and to the interplay of shear and tension during rock failure.

Nevertheless, dilatancy of rock structures similar to that described by Farmin for the Grass Valley veins may have resulted from some cause other than injection of a concentrated "quasi-magmatic" fluid. Several prominent features in the laminated veins of Bendigo suggest that actual dilatation by spreading of foliated leaves and ribbons took place prior to the deposition of quartz.

1. Where adjacent, parallel laminae of slate are coated by a thin ankerite crust it is likely that the laminae spread apart before the introduction of ankerite and quartz, and that subsequently these minerals were deposited as crusts on the laminae (Fig. 12).

2. Tiny vugs with projecting euhedral crystals of quartz are common in many of the quartz bands. Although it is possible that these may represent an excess of solution over deposition during the replacement process, it is also possible that they represent open-space deposition with incomplete filling of the space between parallel laminae.

3. Actual spreading apart of laminae is suggested in many places by the geometric shape and position of the leaves, ribbons, and crinkly bands. In many places it appears that, if the quartz bands were removed, the leaves could be fitted together with a fairly reasonable matching of walls, allowance being made for frayed ends, slight replacement, and broken laminae.

In Figure 13, for example, two parallel slate ribbons, about 1/12th of an inch apart, trend from parallelism with the adjacent bands, diagonally across a quartz band from one wall to another. If the quartz were removed and the laminae pushed together, they would parallel the other laminae and would match fairly well.

Where lines of discontinuous slate slivers in the form of dots and dashes make up the laminae, the structure in most places was caused by replacement. However, in certain examples it may have resulted from the fact that sections of the original laminae remained in their original position on the adjacent wall when parts of the laminae spread apart.

4. Many of the "spread" laminae have been ruptured, with part of the ribbon or crinkly band removed so that broken stubs project out into quartz. Excellent examples are illustrated in Figures 13 and 41. Some of the stubs are coated with ankerite on one or both sides of the projecting ribbon.

5. Spacing of the laminae with respect to the walls of the veins may be significant. It is possible that the thicker, more numerous leaves adjacent to the vein walls, taken together with the narrower, more widely spaced ribbons

and crinkly bands in the centers of the veins, may be an indication of initial dilatation as well as of increased replacement activity in the vein channels.

6. Brecciated laminae, where angular fragments of slate have been rotated from their original positions, are rather common (Figs. 11, 24). This suggests that brecciation of brittle slate laminae occurred during dilation of foliated rock and was followed by cementation by quartz or ankerite.

The structural and textural relations of the laminae suggest, therefore, that dilatation of laminae, or separation of wall-rock partings, may have taken place prior to the introduction of quartz. The dilation, however, may be the result of causes other than the injection of a quasi-magmatic fluid. The injection of dilute hydrothermal solutions under high pressure may possibly have caused spreading apart of the walls with separation of laminae; or, alternatively, hydrothermal solutions may have gained access to the beds and shear planes during the later stages of compression, and acted as a hydraulic press, pushing apart beds or sheared laminae in low-pressure ground while being "squeezed out" in high-pressure areas.[54] These possibilities, however, do not seem likely. It is more probable that dilation was caused by local tensional stresses which resulted from reverse faulting superimposed on the folded rocks. The orientation and relation of shear and tension fractures are in accord with this idea. Obviously, this mechanism would necesitate deposition of quartz nearly simultaneously with the development of openings, or very soon thereafter.

Once spreading of leaves or ribbons had taken place, open spaces between the laminae were filled and the leaves were cemented together; at the same time there may have been minor replacement along the walls, and of particular slate bands.

Evidence against other processes. With the exception of force of growing crystals, which Dunn and Taber have advocated to explain the origin of the Bendigo quartz bodies, McKinstry and Ohle [55] have effectively presented the arguments, pro and con, for the various processes that have been proposed to explain book structure and ribbon structure. These need not be elaborated here. That force of crystallization had some part in the formation of saddle reefs was first proposed by Dunn,[56] who suggested, as an alternative possibility to the filling of lunate cavities by silica-bearing solutions, that:

> . . . the saddle reefs filled cavities, more or less occupied by fragments broken off by the disruption of the beds along the axes, the quartz filling the interstices first, and then exerting enormous pressure to increase its bulk in a manner common to all substances when crystallizing.

A similar mechanism was invoked by Dunn to explain the leg reefs, for in part he said:

> The solutions of heated waters charged with silica were under great pressure, and would consequently penetrate the minutest fissure or crack. Once the silica began to deposit, the crystallizing force would be exerted to widen and enlarge the joint . . . it occupied, the rift extending as the quartz accumulates.[57]

[54] Personal suggestion by W. S. Burbank.
[55] McKinstry, H. E., and Ohle, E. L., Jr., op. cit.
[56] Dunn, E. J., op. cit., Part II, p. 22.
[57] Dunn, E. J., Idem, pp. 23–29.

Taber [58] cites these statements of Dunn to support his contention that force of growing crystals has been an imporant factor in the origin of quartz veins in general and in the Bendigo saddle reefs in particular.

Moreover, he utilized the principle to explain the origin of laminated quartz, for in discussing the origin of saddle reefs he stated:

> The veins have largely made room for themselves by mechanically displacing the wall rocks. . . .
> . . . Where the solutions penetrated along closely spaced planes of bedding or schistosity, the thin layers and films of slate were more or less silicified, and at the same time they were gradually separated as the veins increased. The laminated quartz originated chiefly in this way.

It is well known that under certain circumstances growing crystals do exert force, within the limit of their crushing strength, upon confining structures.[59] Ice veinlets in wet clay and gypsum veins in gypsiferous shales, for example, apparently grow by pushing their walls apart. Although veinlets of this type may form in a near-surface environment and the force may be sufficient to spread the walls of veins under conditions of light load, it is extremely doubtful that the linear force of growing crystals is sufficient to form fissures of the type commonly associated with most hydrothermal veins. Most veins either have structures, such as crustification banding, which preclude force of crystallization as the spreading mechanism, or lie at great depth where closing pressure or length of veins indicates that crushing strength of minerals is exceeded. Where spreading of walls has obviously taken place, the opening probably has been caused by tensional stresses exerted by outside forces rather than by the force of growing crystals within the vein channelway. Most advocates of the force of growing crystals as a mechanism of vein growth find it necessary to postulate that the mineral ingredients are derived from the adjacent walls; lateral secretion in veins of the hydrothermal type, however, has been largely discredited. In view of these objections, one can only conclude that the linear force of growing crystals does not appear to be even a possible explanation of the openings occupied by saddle reefs at Bendigo, or to aid in any way in deciphering the origin of laminated quartz.

(*d*) *Replacement breccias.*—Many excellent examples of replacement breccias occur in the Bendigo quartz bodies, particularly in the "backs," leg reefs, fault reefs, and parts of the saddle reefs. Angular to rounded inclusions, both supported and unsupported, are abundant and range in size from a fraction of an inch to several feet across. That these breccias have formed by replacement is demonstrated in many places (Figs. 5, 19 and 20).

An excellent example of replacement breccia is shown in Figure 5. Here a curving zone of angular to rounded slate inclusions, approximately 4 feet thick, follows the arch of an anticline beneath an asymmetrical body of massive white quartz. From their geometric continuity, it is apparent that the inclusions

[58] Taber, S., Discussion: Econ. Geol., vol. 13, pp. 538–546, 1918. Also, Pressure phenomena accompanying the growth of crystals: Nat. Acad. Sci. Proc., vol. 3, pp. 297–302, 1917.

[59] Becker, G. F., and Day, A. L., The linear force of growing crystals: Washington Acad. Sci. Proc., vol. 7, pp. 282–288, 1905.
Taber, S., The mechanics of vein formation: Am. Inst. Min. Met., Eng. Trans., vol. 61, pp. 1–36, 1920.

represent a single slate bed that was first brecciated and later cemented by quartz. The shape and distribution of the fragments indicate that the slate bed was broken by a network of irregular fractures along which quartz was deposited and slate was replaced. Where the veinlets are narrow, the fragments are angular and can be roughly fitted together; where the veinlets are wider, the fragments have more rounded outlines and in places are unsupported. As replacement progressed, the individual fragments apparently became more and more rounded, and at the same time more and more isolated. Thus the progressive stages, illustrated in this figure, indicate that the unsupported inclusions, whether angular or rounded, are products of incomplete replacement.[60]

The magpie quartz, chloritic quartz, and mottled quartz, previously described, are in reality breccia types that illustrate the progressive change that took place in the wall-rock fragments. In magpie quartz, for example, the fragments are clearly recognizable as shale or sandstone (Fig. 20). Chloritic quartz developed in the next stage, and the rock is no longer recognizable as such, but consists largely of light- to dark-green chlorite, the intensity of the color depending directly on the amount of chlorite in the quartz. Intermediate stages are common where slate fragments are partly altered to or surrounded by chlorite with quartz encroaching on the chlorite (Fig. 19).

Mottled quartz represents the final stage of the replacement process. All traces of the original rock have disappeared, as have the sericite and chlorite. Only carbonaceous residues remain that mark the outlines of the original fragments and give the quartz a slightly discolored or mottled look.

Although rock alteration in the usual sense has generally not affected the slate or quartzite beyond the immediate contacts of the quartz bodies, and although the limits between quartz and slate or quartzite are usually sharp, extensive alteration of the rock fragments has taken place within the quartz bodies themselves. This alteration may have been caused by the large volume of ore solutions that flowed through the permeable channelways. In the more solid wall rock, flow of solutions was restricted and the rocks were replaced with difficulty.

The progressive alteration of rock fragments may be readily traced in thin sections under the microscope. Stillwell[61] first observed from his microscope work clear evidence of the alteration of slate to "white mica" (sericite), and of "white mica" to chlorite. It is also generally clear that chlorite has been replaced by ankerite and that quartz replaced ankerite and chlorite, and probably sericite (Figs. 18, 19, 20, 37).

This sequence of hydrothermal alteration is not everywhere observable, but it can be inferred from a study of the alteration products where they are well developed. The alteration of slate to sericite is readily seen megascopically in many places, and it is apparent in some of the thin sections where chlorite is prominent. The alteration of sericite to chlorite is obervable where both oc-

[60] Bateman, Alan M., Angular inclusions and replacement deposits: Econ. Geol., vol. 19, pp. 504–520, 1924.

[61] Stillwell, F. L., Replacement in the Bendigo quartz veins and its relation to gold deposition: Econ. Geol., vol. 13, pp. 100–111, 1918.

cur together, although replacement in the usual sense is not demonstrated by textural relations such as are found in ore minerals, but rather by a decrease in the relative amount of sericite and an increase in chlorite within a restricted area. This may mean that alteration is effected by a chemical reaction in which sericite is dissolved and chlorite precipitated without the molecule-for-molecule relations characteristic of the replacement process.

Evidence of replacement of chlorite by ankerite, although not abundant, is unmistakable. Furthermore, evidence of replacement of ankerite by quartz is widespread and convincing. Replacement veins of quartz cutting ankerite are abundant, and contacts between ankerite and quartz show quartz encroaching on ankerite.

This sequence of mineralogical changes possibly provides a partial explanation of the replacement of slate by quartz, a process which Lindgren [62] and others have seriously questioned. Although in many places in the Bendigo veins quartz appears to have replaced slate, it may not have done so directly; the quartz may have replaced ankerite, chlorite, or sericite, which had previously replaced slate. At Bendigo the sericite-chlorite-carbonate alteration would seem to be an advance phase of the mineralizing process, which was followed by vein quartz, as suggested by McKinstry and Ohle.[63]

The sequence also explains why in places ankerite replaces wall rock and in other places coats it in a crustification texture. Where sericite or chlorite is present, replacement by ankerite may take place; where it is absent, ankerite does not react with the wall rock but coats it, and sharp boundaries between wall rock and ankerite occur. The sharp boundaries between wall rock and quartz may be explained in the same way.

(*e*) *Sulfide replacement.*—In addition to formation by replacement of sericite, chlorite, and carbonates, products of wall-rock alteration, the sulfide minerals and gold have clear-cut replacement textures. Arsenopyrite and pyrite, both pre-vein quartz in age, clearly replaced fresh sandstone and slate in disseminated crystals around the margins of the quartz bodies and in the inclusions contained in the massive quartz. Pyrrhotite, chalcopyrite and galena replaced quartz, ankerite, and chlorite within the quartz bodies. These were apparently deposited at approximately the same time and form an overlapping sequence. Native gold was clearly deposited later than all the gangue and sulfide minerals, with the exception of a small amount of very fine-grained late pyrite. Gold follows tiny cracks in quartz, ankerite, and the sulfide minerals in the form of veinlets, and is present as hackly masses, rounded "shots," and disseminated grains in massive quartz, particularly in the spur reefs. The disseminated grains tend to be localized along the slate laminae in ribbon quartz and along the contacts of quartz with slate or of quartz with ankerite crusts. Its replacement origin is apparent in many places and it is clearly a very late mineral. Thus the localization of sulfides and gold substantiate the conclusion that replacement played an important part in the formation of the Bendigo ore bodies (Figs. 43, 44).

[62] Lindgren, W., Magmas, dikes and veins: Am. Inst. Min. Met. Eng. Trans., vol. 74, pp 83 and 91, 1926. Also, Mineral Deposits, p. 180, McGraw Hill Book Co., New York, 1933.
[63] McKinstry, H. E., and Ohle, E. L., op. cit.

(3) *Evidence of Growth by Accretion.*

Although it is well established that the greater part of the faulting that localized the Bendigo bodies preceded the deposition of quartz and other products of hydrothermal mineralization, abundant evidence indicates that movement on both bedding-plane faults and crosscutting faults was intermittent and repeated, and that "growth by accretion," to use Hulin's [64] term, played an important part in the formation of the quartz bodies.

(a) Striations and slickensides trending in several directions are a common feature along fault walls. As many as five directions of movement have been detected along a single fault zone in the Monument Hill mine by peeling off successive layers of sheared rock. In places the striae trending in several directions may have been caused by oscillatory movement, but in general the striae are persistent enough to indicate well-defined directions of movement.

(b) Well-defined faults offset by later faults, which in places are offset by still later faults, prove that movement itself was intermittent. These relations are particularly well shown where two or more strike faults of opposite dip intersect above the crest of an anticline (Fig. 1). Much of the repeated fault movement may have preceded the deposition of quartz; two specific examples cited by Stillwell,[65] however, prove that some of it at least occurred as intermineralization fracturing. These examples are "(1) faults which form a saddle reef in centre country intersect and displace the 'backs' of other saddle reefs when traced upwards, and (2) the reef is often intersected by a fault which has slickensided and polished the quartz, and whose course through the reef may be indicated by a white pug [gouge] [66] consisting of finely-powdered quartz."

(c) Two or more parallel laminated quartz veins separated by seams of gouge 1 or 2 inches thick are common and indicate that more than one period of movement took place along the bedding-plane faults (Figs. 6, 10). Although not abundant, gouge seams in places cut across laminated quartz veins from one wall to another, indicating post-quartz movement. A few examples of laminated veins cutting across similar earlier veins have been observed. This intersection of banded structures, together with sheeted, polished, or crushed quartz, is strong evidence of repeated intermineralization movement.

(d) Sheeted fractures that cut massive vein quartz parallel to vein walls are rather common (Fig. 21).

(e) In places spurs dipping at a low angle cut across the laminated quartz and are interpreted as the filling of tension openings which formed after the sheared rock along bedding-plane faults was replaced by quartz. This relationship may be seen locally on a large scale underground. Figure 18, however, shows a similar relation in hand specimens where horizontal quartz veinlets cut across laminated slate and ankerite. In this specimen the quartz is post-

[64] Hulin, C. D., Structural control of ore deposition: Econ. Geol., vol. 24, no. 1, pp. 15–49, 1929.

[65] Stillwell, F. L., The factors influencing gold deposition in the Bendigo gold field (Part III): Commonwealth of Australia Advisory Council of Science and Industry Bull. 16, p. 18, 1919.

[66] Writer's insert.

ankerite in age, and intermineralization fracturing took place, at least locally, between the ankerite and quartz stages.

(f) Phantom veinlets of clear quartz that cut the earlier massive quartz are direct evidence, not only of late fracturing, but also of more than one generation of vein quartz (Figs. 21, 22, 23). It is not uncommon to find native gold following phantom veinlets or filling the tiny gash fractures which accompany the phantom veinlets.

(g) Small fractures and cracks in the vein quartz followed by veinlets of pyrite, chalcopyrite, galena, sphalerite, and gold are locally abundant (Figs. 42, 43). These occurrences seem to justify the conclusion recently made by Ebbutt [67] that "late minor and highly localized structures within the deposit itself [are] extremely important in the localization of gold." This minor fracturing superimposed on earlier vein minerals is undoubtedly an important factor in maintaining permeability during vein formation; it accounts to some extent for the presence of sulfides and gold in otherwise barren quartz veins.

(h) Microbrecciation of sulfides, particularly arsenopyrite and pyrite, is a common feature (Fig. 38). Brecciated sulfide fragments are commonly angular, in places show evidence of rotation, and are cemented by later quartz.

(i) Pronounced strain shadows and wavy extinction are common microscopic features of the vein quartz. Microbrecciation of the quartz, however, seems to be a localized feature and is not common in thin sections.

Unsupported wall-rock fragments and book structure are interpreted elsewhere by Hulin, Johnston,[68] and others as indicative of intermineralization brecciation, fracturing, and vein reopening. Although these are prominent features in the Bendigo quartz bodies, they are better explained by other processes; in fact, there is evidence that they were not caused by intermineralization fracturing.

From the above evidence it is clear that minor faulting, fracturing and brecciation took place during the formation of the saddle reefs and related bodies. This fact was recognized by Stillwell [69] who concluded,

> It is clear . . . that there have been rock movements, fracturing, and deposition of quartz after the main deposition of the reefs. In some cases the reefs and spurs have been fractured, and in other cases there has been subsequent movement along fault planes from which mineralization had previously extended.

Stillwell, apparently, did not attach great importance to these features, and was more inclined to emphasize replacement (and force of growing crystals) as the predominant process of reef formation. Stone,[70] on the other hand, was more impressed by the evidence of intermineralization fracturing, for he concluded,

> The quartz bodies themselves furnish arguments for growth by successive additions and consequently for renewed faulting. This is true of the laminated quartz veins

[67] Ebbutt, Frank, Relationships of minor structures to gold deposition in Canada, *in* Structural Geology of Canadian Ore Deposits: Canadian Inst. Min. Met., pp. 64–77, Montreal, 1948.

[68] Hulin, C. D., Structural control of ore deposition: Econ. Geol., vol. 24, pp. 15–49, 1929. Johnston, W. D., Jr., Vein-filling at Nevada City, Calif.: Geol. Soc. America Bull., vol. 49, pp. 23–34, 1938.

[69] Stillwell, F. L., op. cit., Bull. 8, pp. 21–22, 1918.

[70] Stone, J. B., op. cit., p. 890.

also. Most reefs are too big to represent open-space filling at one time and, while there is evidence for replacement locally, a more plausible view is that the reefs grew by small accretions coincidentally with continued compression and repeated faulting.

The fact that quartz bodies of the type present in Bendigo may have formed by "repeated fillings of small openings produced recurrently by intermineralization fault movements" was suggested by Hulin [71] himself, in his original paper on this subject, for he states, ". . . the ore shoots of saddle reefs, like those of vein deposits, have formed through the process of accretion, the locus of ore deposition being dependent on the brecciation and reopenings produced by intermineralization faulting. . . ."

Although evidence of accretion is abundant, it should be pointed out that this evidence appears at a relatively late stage in the formation of the quartz bodies. As Hulin [72] pointed out:

> Evidence of the intermineralization brecciation occurring just previous to the introduction of the late metallic minerals is usually the most apparent. Here a change in the nature of the material being deposited before and after the brecciation lends contrast. Even here, however, replacement of the borders of the early quartz fragments by the later metallic minerals results in rounded and irregular outlines and borders, with a consequent masking of evidence.

This observation applies very aptly to Bendigo. Unless evidence of accretion has been masked by recrystallization or by replacement, it is likely that vein reopening and brecciation took place after the major quartz bodies had formed. The effect of the accretion process was to maintain permeability so late solutions carrying some silica, sulfides, and gold gained access to the otherwise solid quartz bodies.

The fact that recrystallization may have destroyed early evidence of the accretion process was suggested by Stone [73] who concluded: "It is possible that the late quartz veins that can be seen are only the last of a succession of such veins, but that recrystallization has destroyed evidence of earlier ones." It may be convenient to call on recrystallization to explain features that are now unobservable, but recrystallization as a process would be more convincing if precise evidence of such a process were presented or observable.

CONCLUSIONS ON ORIGIN.

The evidence is good, therefore, and the conclusions well founded, that open-space filling, replacement, and the accretion process played important roles in the formation of the Bendigo quartz bodies. It would be instructive to know as well the relative importance of each process. Although it is probably impossible to answer this question quantitatively, considerable progress in understanding the origin of the quartz bodies can be made by relating the textural varieties of quartz, as well as other manifestations of the three processes, to their relative positions in the Bendigo fracture pattern. Because the initial

[71] Hulin, C. D., Structural control of ore deposition: ECON. GEOL., vol. 24, no. 1, pp. 15–49, 1929.
[72] Hulin, C. D., op. cit., p. 26.
[73] Stone, J. B., op. cit., p. 890.

localization of the quartz bodies was determined by the vagaries of a fracture system superimposed on the folded rocks, a correlation of the fracture types with the evidence for open-space filling, replacement, and growth by accretion provides data on the type of failure that took place, as well as information on the nature and orientation of the deforming stress.

Vug, druse and comb textures, domino breccia, crustification banding, and spreading of wall-rock structures—textures and structures usually indicative of open-space filling—are abundantly developed in the centers of saddle reefs and in the spur reefs. These textures and structures are associated with fractures characteristic of tensional failure; it is inferred, therefore, that the openings, where they are well developed, were caused by tension.[74]

On the other hand, evidence of replacement—selective metasomatism of particular beds and drag folds; irregular spurlike quartz bodies; laminated quartz; partly digested inclusions; and textural relations of individual minerals —is more abundant on the limbs of folds, along "backs" and leg reefs, in fault reefs and neck reefs, and around the lower margins of saddle reefs. These textures and structures are in themselves indicative of or are associated with fractures or foliation planes that are characteristic of shearing. Where these features are well developed it is inferred that permeable zones were caused by shear failure.

Concerning the origin of the fracturing at Bendigo, it has been concluded on the basis of the attitudes of the planes of shearing and the tension fractures, together with the known direction of movement on the fractures, that the plane of maximum stress was essentially horizontal and that fracturing took place in "response to stresses whose effect was to compress the rock mass horizontally and to extend it vertically." [75] Failure resulted in conjugate faults which followed bedding planes on the limbs of folds with more or less horizontal tension fractures superimposed on the folded rocks. (Stress diagram, Fig. 1). At the intersection of the conjugate faults above the crests of anticlines the beds were dragged apart, because here bedding was roughly parallel to the plane of maximum stress, and the offset on the faults was such as to create a triangular opening at the crest of the folds. These openings were subsequently filled by quartz to form the saddle reefs. Because the plane of maximum stress was essentially horizontal, and the direction of easiest relief was upward, horizontal tension cracks and gash-shaped fractures formed either as independent breaks on the limbs of the folds or as components of shearing. These openings provided receptacles for the formation of the spur reefs.

It is clear in many places that tensional failure was followed by open-space filling and that shearing was followed by replacement. The quartz bodies, therefore, tended to form by open-space filling where tensional openings existed

[74] McKinstry, H. E., Structural control of ore deposition in fissure veins: Am. Inst. Min. Met. Eng. Tech. Pub. No. 1267, Jan. 1941.

[75] Stone, J. B., The structural environment of the Bendigo goldfield: Econ. Geol., vol. 32, pp. 867–895, Nov. 1937.

The cause of fracturing at Bendigo has been analyzed in accordance with modern concepts by Stone and McKinstry, and for details reference is made to the publication above and to the following:

McKinstry, H. E., Bendigo, Victoria, Australia: Ore Deposits as Related to Structural Features, Princeton Univ. Press, Princeton, N. J., pp. 160–162, 1942.

and by replacement where permeable zones resulted from shearing. This is not to say that open-space filling was not accompanied by minor replacement activity locally and that replacement was not accompanied by some open-space filling, particularly where open spaces resulted from tensional components of shear. The relative importance of the two processes, however, depended on the nature of the deforming stress and the type of fracture or opening with which a particular quartz body was associated.

Features indicative of growth by accretion are found in quartz bodies associated with both shear and tension. Because evidence of this process appeared at a relatively late stage in the formation of the quartz bodies, it may be considered that intermineralization fracturing and brecciation, and deposition of late quartz, sulfides, and gold, were superimposed on the quartz bodies that formed by replacement and open-space filling. In general the stresses that caused vein reopening appear to have been oriented in essentially the same way as those that caused the initial fracturing and faulting. Moreover, it is likely that the intensity of the late fracturing varied considerably from place to place. Because the localization of the gold ore shoots was probably dependent on the late fracturing, brecciation, vein reopening, and late mineralization, specific knowledge of the intensity and distribution of these features would probably go a long way toward answering one of the unsolved problems of the district: the origin, localization, and position of the high-grade ore shoots.

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SEDIMENTATION: AN APPROPRIATE FIELD OF RESEARCH IN THE NATURAL HISTORY OF COAL BEDS.[1]

E. C. DAPPLES.

ABSTRACT.

Potential studies in the accumulation of coal-bearing strata as being important in further understanding the natural history of coal are discussed. These lines of approach include regional isopach studies of the stratigraphic unit containing coals, and the individual coal beds; bulk petrographic and lithofacies studies of the non-coal strata; biofacies and ecologic studies; and, tectonism during the deposition of the sedimentary units concerned.

INTRODUCTION.

INVESTIGATIONS bearing upon the geologic history of coal show distinct cleavages in subject grouping such that they are readily organized under four major regimes. These can be identified as (1) coal botany, (2) coal chemistry, (3) coal petrography, and (4) coal stratigraphy. With the exception of coal stratigraphy these fields of research are sufficiently specialized so that they remain peripheral to the training and experience of all but a few professional geologists. Moreover, knowledge within these realms has been extended beyond the limits where the geologist can contribute substantially. Almost precisely the opposite can be said about coal stratigraphy, and its associated field of coal sedimentology, which offer much to be investigated by the geologist. This is particularly true in view of the contribution to be made by an increased understanding of the petrology of the rocks with which coal is associated. Indeed, if we are to know more about the natural history of coal we must first learn more concerning the broad framework in which the coal bearing beds occur; and, the petrographic relationship between the strata of the "coal measures" and those of their time-stratigraphic equivalents in non-coal areas. Within the generalized framework detailed studies of local coal occurrences can be appraised in their proper magnitude. With the viewpoint in mind of arousing interest in studies in coal sedimentation, I plan to review some lines of important research which only the geologist can pursue; and which establish the position of coal as a lithology narrowly defined by certain depositional conditions.

ISOPACH STUDIES.

The framework within which areal studies must be placed is the isopach map. With few exceptions (10) [2] detailed isopach maps of large areas of selected time-stratigraphic units are absent in the published accounts of coal

[1] Presented before the Society of Economic Geologists, Committee on Coal Research, November, 1948.

[2] Numbers in parentheses refer to Bibliography at end of paper.

bearing regions. Such maps, which should include both the coal bearing strata and their stratigraphic equivalents elsewhere, display the structural conditions prevailing during the interval of deposition. The coal bearing areas can be distinguished by suitable colors or patterns from areas where other continental or marine sediments accumulated. The result is a clearly visible representation of (a) the areas of coal accumulation; (b) the shape of the basins of deposition and their areal distribution; (c) the structural framework existent during coal deposition; (d) the position of the coal bearing strata with respect to possible sources of the sediments.

LITHOFACIES STUDIES.

The investigations of Wanless (8, 9) have demonstrated the pronounced association of coals with other strata in cyclical repetition. The number of such coincidences is so large that a strong probability exists that cyclical sedi-

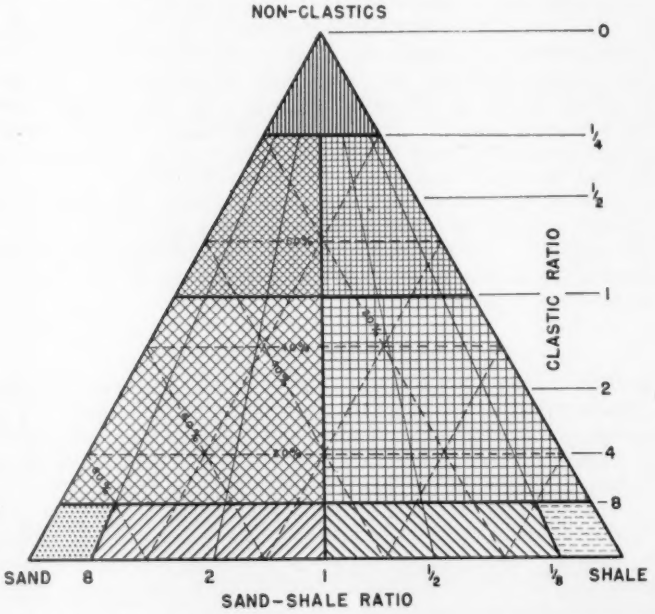

FIG. 1. Lithofacies triangle showing by pattern differences nine gross lithologic types. Note how these are defined by clastic ratio and sand-shale ratio limits. (After Krumbein.)

mentation must have a direct bearing upon large scale coal accumulation. In this connection additional information is needed concerning the variations and the causes of this cyclical sedimentation. The very excellent work of

Wanless (10) indicates the range of typical cycles in Pennsylvanian beds in the Appalachian coal fields. Obviously this range in cyclical types creates problems in stratigraphic correlation, and consequently the re-construction of the depositional history is confused. However, if several individual cycles are grouped together into a single stratigraphic unit, the lateral variations in lithology become subject to statistical interpretation; and, the requirements of stratigraphic correlation are not so exacting. Certain attributes can be plotted graphically and are suitable for contouring on a map. Krumbein (3) has devised a method of assigning numerical values to selected lithologies. This method employs an equilateral triangle, the corners of which represent, respectively, non-clastics (other than coal), sandstone, and shale. If for any selected stratigraphic interval the thickness of total clastics in any measured outcrop section, or well log, is divided by the total non-clastics, a ratio results (the clastic ratio). This is a value suitable for plotting on a map, and, contours may be drawn through points of equal clastic ratio. Similarly the sand-shale ratio can be determined and a second group of contours drawn. Figure 1 is a triangle in which intervals of clastic ratio and sand-shale ratio have been selected to represent nine types of gross lithology. Areas representative of these lithologies can be similarly shown on maps. From such maps regional changes in lithofacies of groups of cyclothems are subject to analysis and interpretation. Areas of rapid lithofacies changes become apparent and their significance can be examined from the viewpoint of the rate of total deposition, thickness, types, and ranks of coal.

Triangles of statistical lithologies can be made using other end members. For example coal can be placed in the non-clastics apex and a clastics-coal ratio be prepared. Maps of such attributes will doubtless show interesting and illuminating relationships between the amount and type of clastics and the accumulation of humic matter.

BULK PETROGRAPHIC STUDIES.

Recently Krynine (5) has demonstrated the value of plotting sedimentary lithologies in terms of end members represented by the corners of a tetrahedron. Figure 2 prepared by Krumbein (4),[3] is an experimental plot of a typical western Illinois cyclothem with the humic end members of the tetrahedron pointed toward the observer (the percentage of humic matter is indicated by the size of the small triangle at the plotted point). Note the changes in plotted positions on the triangle for the members of a typical cyclothem of western Illinois. Such tetrahedrons can be effectively employed in quantifying the bulk petrographic properties of the coal bearing beds and in establishing the similarities between cyclothems.

TECTONIC CONTROL STUDIES.

Evidence is accumulating rapidly that many commonly occurring types of sandstone, shale, and limestone have pronounced affinities and are mutually ex-

[3] Prof. Krumbein has kindly permitted the author to use this illustration prior to its appearance under his name.

clusive to other associations. Moreover, the tectonic condition of the depositional areas appears to be a prime factor in controlling the sedimentary type. Table 1 (1) is a tabulation of these associations. Strata associated with coal are shelf types and appear to be of the mildly unstable shelf where tectonic conditions alternate between stable and unstable conditions. Somewhere in this framework conditions favorable for the accumulation and preservation

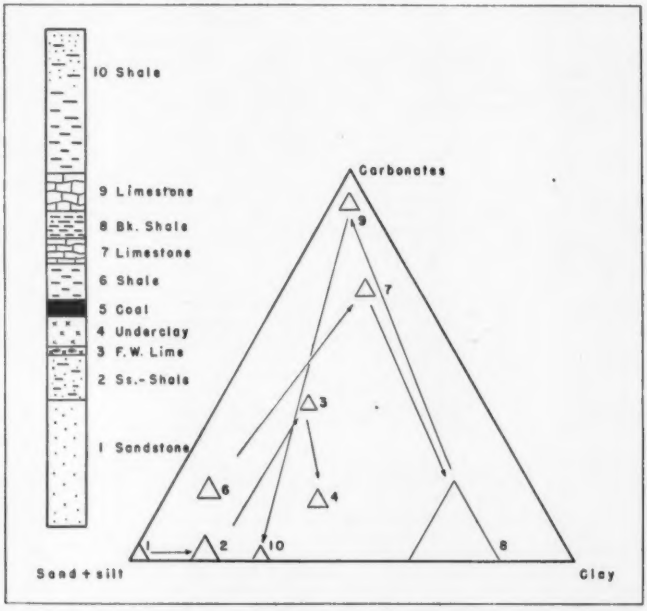

FIG. 2. Face of end-member tetrahedron showing variation in constituents of units of a typical cyclothem of the Pennsylvanian of western Illinois. The size of the small triangles indicates the percentage of humic matter present in each unit. Unit 5, the coal, is not shown since it would constitute the dimensions of the large triangle. (After Krumbein.)

of vegetation make their appearance, and much detailed petrographic work remains to be done to evaluate and fully comprehend the significance of this control.

Such an outlook based upon the tectonics poses a question. How are coal forming localities distributed with respect to large positive, negative, and stable areas existent during such times? Herein lies a fertile field for petrographic interpretation of the type being pioneered by Krynine (5). Investigations of this type should lead to the establishment of criteria for recognizing the then existent shore lines, source areas of sediments, types of coal deposited in

TABLE 1.

SUMMARY OF LITHOLOGIC ASSOCIATIONS.

Observed sedimentary associations			Inferred tectonic framework	
Clastics		Non-clastics		
Sandstones	Shales	Limestones, et cetera	Depositional area	Source area
Pure quartz Quartz-glauconite Quartz-iron oxide Quartz-muscovite	Chiefly claystones; any colors; calcareous, glauconitic, carbonaceous; quartz common in silt	Normal marine Fragmental Foraminiferal Secondary chert and dolomite Random reef distribution	Stable shelf	Stable to mildly epeirogenic
Quartz-potash feldspar "Blanket" arkose Quartz-muscovite (subgraywacke)	Chiefly siltstones; any colors; micaceous; carbonaceous; feldspar may be common in silt	Nodular, with uneven bedding Dense, argillaceous	Mildly unstable shelf	
Subgraywacke	Chiefly siltstones; any colors; micaceous, calcareous, siliceous, carbonaceous; variety of minerals in silt	Thickened shelf types Evaporites (primary dolomites, sulphates, chlorides) Marginal reefs	Intracratonic basin	Stable to strongly epeirogenic
"Wedge" arkose	Red, chocolate; silty, micaceous	Nodular limestones Special evaporite sequences		Strongly positive
Graywacke	Chiefly siltstones; any colors; chloritic, siliceous, micaceous, carbonaceous, pyritic; large variety of minerals	Thick, dense, dark, siliceous	Geosyncline	Strongly orogenic

areas of particular tectonism, and concentrations of coal material in thick continuous beds as against thin beds of sporadic distribution.

ECOLOGIC STUDIES.

Much remains to be investigated concerning the depths of water and elevations above and below sea level during the accumulation of the coal bearing strata. Data are needed on the ecologic communities as indicated by the fossil assemblages and the associated petrography of the rocks in which they are entombed. An example of the approach is the work of Elias (2) who used the floral and faunal relationships to establish depth of water zones in which strata of the Big Blue series accumulated. An understanding of the more complex variations in deposition of units of most of the coal cyclothem will in turn provide us with a much clearer insight of the physical limitations of coal deposition.

CYCLOTHEM STUDIES.

It has not been clearly established how deposition has varied as the units of the cyclothem change regionally. Figure 3 is an attempt to show graphically the inter-relationship between depositional environments, clastic deposition, and tectonic condition prevalent during the accumulation of a typical coal cyclothem of western Illinois. In the upper half of the diagram (A) the ordinates represent probable elevations above sea level, whereas, the abscissae represent the progress of time during the deposition of the single cyclothem. The dashed lines represent the elevation of the surface upon which deposition is taking place (depositional interface), and, hence, indicate the dominant en-

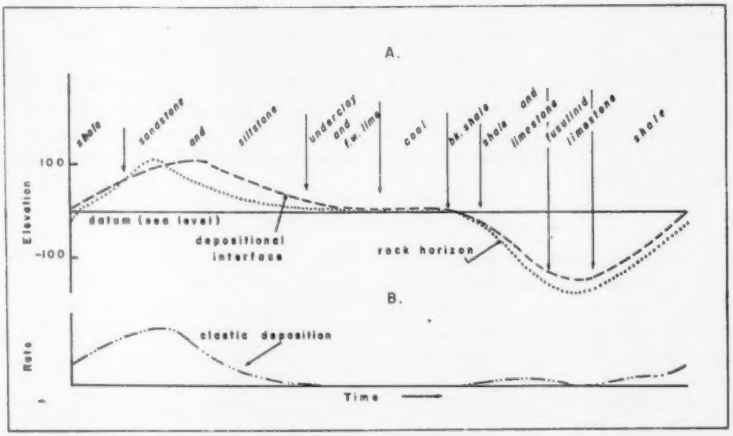

FIG. 3. A. Diagram showing probable position of surface of deposition during the accumulation of units of a typical Pennsylvanian cyclothem of western Illinois (dashed lines); and the diastrophic changes in the same area as indicated by the position of some arbitrarily selected rock horizon below the surface of deposition (dashed lines). B. Diagram showing rate of clastic deposition during the accumulation of sediments in A.

vironment, continental or marine. The dotted line represents the elevation of some arbitrarily selected rock horizon immediately below the base of the cyclothem and serves as a reference datum of the tectonic condition. If the line rises, the area is experiencing an increase in positive tectonism, if it declines, the area is experiencing negative tectonism, and if it remains level, the area is stable. The lower half of the diagram (B) indicates the rate of clastic deposition (ordinate) during the progress of the total sedimentation (abscissae). The clastic depositional rate increases rapidly in the early stages of the cycle and reaches a maximum in approximately the middle of the basal sandstone deposition, and then slowly decreases as the fresh-water limestone accumulates. Obviously the period of coal deposition is one which is noteworthy by the absence of clastic deposition. Following the accumulation of

the coaly matter clastic deposition is again resumed, but to a limited degree, and declines again to a very low value during the deposition of the fusulinid limestone. The increase in clastic matter following the accumulation of the fusulinid limestone accompanies the diastrophic change as indicated in Figure 3A by the position of the reference rock horizon. Considerable significance should be attached to the fact that the periods of non-clastic deposition are also the periods of maximum tectonic stability. In this connection it is rational to suggest that if a period of tectonic stability is achieved when the depositional interface lies below sea level that a fusulinid limestone develops, whereas, if the depositional interface is slightly above sea level coal accumulates. If such is the case, coal should occur in the position of the fusulinid limestone in those areas that are marginal to the sea during the periods of fusulinid limestone deposition. Hence, in some areas the stratigraphic equivalent of a limestone should be a coal bed. Are these the "rider" coal beds? Moreover, does a period of tectonic stability control the development of widespread coal beds? Studies following such general lines of thought should supply us with much needed information pertinent to the diastrophic controls in coal deposition, and the reasons for the existence of areally widespread coal beds of surprisingly uniform thickness.

COAL THICKNESS STUDIES.

It is commonplace knowledge that certain coals are surprisingly uniform in thickness over very extensive areas. In fact, this is one of the most characteristic features of the "coal measures." There has been, however, little information published on the character of the variations in thickness of coal beds. Sims, Payne and Cady (7) have drawn isopachs on the Herrin coal in Wayne County, Illinois. Throughout this area the coal shows a pronounced tendency to maintain a thickness of 3 to 5 feet and departures from this thickness are random. There is no tendency toward any consistent thickening or thinning in any direction. Is this the expected behavior of coal beds throughout all the basins, or is it restricted to parts of the basins? Are there any regional trends toward thinning of coal, and, if so, how is such thinning related to other units which constitute the coal cycle? Thinning of the coal should also be examined in terms of the percentage of coal types. Is fusain likely to be more abundant in the thinner coals? Does durain, vitrain, or cannel preferably associate with any regional changes in the thickness of beds?

SELECTION OF THE STRATIGRAPHIC INTERVAL.

If the studies recommended herein are to be pursued, how large a stratigraphic interval must be selected in order to assure reasonably satisfactory results? Obviously the essence of much of the work depends upon the accuracy of the stratigraphic correlation, and significant errors would lead to interpretative disaster. Since the correlation of individual cyclothems is somewhat uncertain, when extensive areas are considered, it is necessary to select a unit clearly defined by operational boundaries. When the unit is delimited by areally widespread recognizable beds, changes within a unit may

be appraised. Selection of a thick unit permits the analysis of the regional aspect, namely, the changes in facies over a large area. Once this is established then the local area and the smaller unit can be properly evaluated. In this connection, the most widespread and easily recognizable strata are those deposited during the interval of tectonic stability, namely, the coal and fusulinid limestone. Hence, these should constitute the operational boundaries of the stratigraphic intervals examined. For example, the interval between two coals, or two limestones, or a coal and a limestone, can be examined in the light of the aspects already set forth.

CONCLUDING REMARK.

The reader is doubtless aware that the purpose of this report has been to enumerate rather than solve some of the problems associated with coal sedimentation. In particular, the aim has been to direct attention to the petrology of the rocks associated with the coal. It is the writer's firm conviction that such an approach will provide a clearer understanding of the processes involved in the natural history of coal.

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EVANSTON, ILL.,
June 17, 1949.

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STRUCTURES DUE TO VOLUME SHRINKAGE IN THE BEDDING-REPLACEMENT FLUORSPAR DEPOSITS OF SOUTHERN ILLINOIS.[1]

ROBERT M. GROGAN.

ABSTRACT.

Flat-lying, elongate bedding-replacement fluorspar deposits in southern Illinois commonly exhibit structural features best explained as the results of net loss of rock volume during the ore forming process.

Synclines found over many deposits are regarded as the results of a thinning of limestone strata localized in the ore-bearing areas. A statistical study of test borings shows that such localized thinning is a characteristic feature of the district. Also many evidences of subsidence are apparent within the deposits, such as measurable thinning and removal of part or all of certain limestone beds, spalling and collapse of slabs of roof-rock and other layers of rock into the body of the deposits, presence of V-structures, and cavities and tabular openings at the sides and tops of deposits.

The mechanism responsible for the indicated volume shrinkage is considered to be in part the stoichimetric replacement of calcite in limestone by denser fluorite, and in part the actual removal of limestone by the action of solvent mineralizing fluids.

INTRODUCTION.

FLUORSPAR occurs in bedding-replacement deposits in the Cave in Rock district of Hardin County, Illinois, a part of the famous Illinois-Kentucky fluorspar mining field (1, 2, 3, 4, 5).[2] Prior to 1916 the greater part of the fluorspar produced in Illinois came from vein deposits, principally those in the Rosiclare district. Since that time, however, an increasingly larger share has come from the bedding deposits, as indicated by the fact that during the period 1940 through 1945 they yielded an estimated 42 percent of the total Illinois production. Because of their importance they received special geologic study during and after World War II.

DESCRIPTION OF DEPOSITS.

The bedding-replacement deposits are found in Mississippian limestones at four principal stratigraphic levels that occur within a vertical distance of 190 feet, extending downward from the top of the Renault limestone to about 75 feet below the top of the Fredonia limestone. The deposits are generally elongate and lie essentially parallel to the plane of stratification of the replaced limestones. Single continuous ore bodies have been mined for as much as

[1] Published by permission of M. M. Leighton, Chief, Illinois State Geological Survey.
[2] Numbers in parentheses refer to Bibliography at end of paper.

2000 feet in the direction of their greatest length and 480 feet at right angles to that direction, although widths of 50 to 200 feet are more common.

Fluorspar is the chief ore mineral, but sphalerite and galena are also of major importance in several deposits. Common accessory minerals include calcite, quartz, barite, chalcopyrite, marcasite, and pyrite. Most of the fluorspar occurs as banded replacement ore in distinct beds that range from a few inches to 3 feet or more thick. Where two or more ore beds are present they

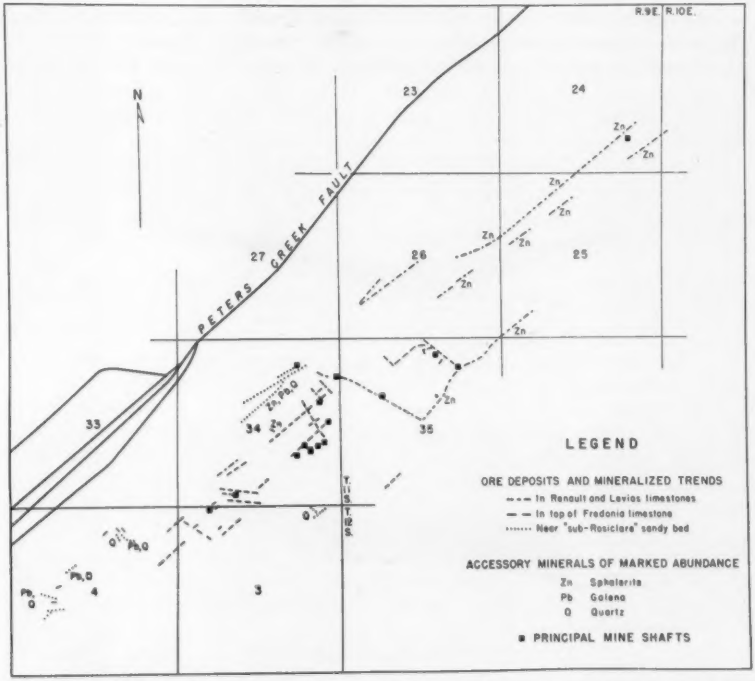

FIG. 1. Principal deposits and mineralized trends, Cave in Rock fluorspar mining district, Hardin County, Illinois.

may or may not be separated by poorly mineralized, unmineralized, or shaly limestone that ranges in thickness from a fraction of an inch to several feet. The aggregate thickness of the ore beds decreases toward the margins of the deposits. Generally the lower ore beds pinch out first, the upper beds last.

The areal distribution of the principal fluorspar deposits and mineralized trends in the Cave in Rock district, the stratigraphic position of the ore, and the characteristic accessory minerals are shown in Figure 1. The deposits are associated with sets of joint-like fractures and of minor pre-mineral faults that have displacements of less than 20 feet, commonly less than 10 feet, all

trending mainly northeast and northwest. Collectively they form a mineralized belt some 4000 to 5000 feet wide which in a general way parallels the over-all course of the Peters Creek fault zone. This zone, with its aggregate downthrow of at least 500 feet to the northwest, is the largest structural feature in the district. Traces of fluorspar, galena, and sphalerite have been found along this fault, and it is commonly assumed that the mineralizing solutions rose from their source in depth along Peters Creek fault and then spread outward laterally and vertically along minor intersecting faults and fractures.

Structurally there are two general types of deposits, namely those in which the ore is disposed more or less symmetrically on either side of a central zone of fracturing or minor faulting, and those in which the ore lies along one

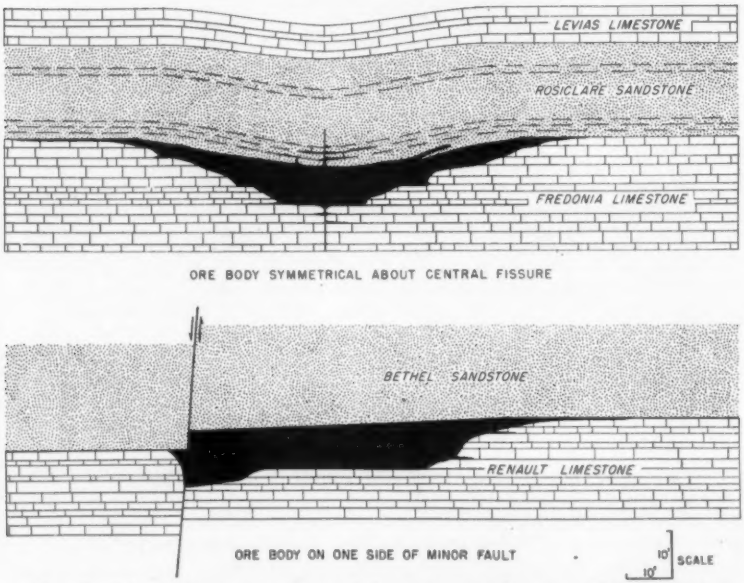

FIG. 2. Schematic cross-sections of the two general types of bedding-replacement fluorspar deposits.

side, generally the upthrow side, of a minor fault. Schematic cross-sections of the two types are shown in Figure 2. In the first type the ore is thickest along or adjacent to the line of axial fracturing and thins toward both margins. Inward-dipping roofs, such as that shown, occur over practically every deposit of this type which is capped by the shaly and relatively incompetent Rosiclare sandstone, but are generally absent where the cap is a structurally competent material like the Fredonia limestone. In the second type the ore is thickest adjacent to the fault and thins toward the far margin. An inward dip of the roof is not so perceptible, although it has been observed in some deposits.

VIEWS OF PREVIOUS INVESTIGATORS.

Previous investigators of the Cave in Rock deposits have generally agreed as to their replacement origin and their localization along joint-like fractures and minor faults. Schwerin and Currier, for example, observed and described certain features suggestive of loss of rock volume such as open spaces between ore and caprock, spalls of caprock entrapped in the underlying ore, and irregular bedding veinlets of fluorspar of the fissure-filling type in shaly roof rock above the ore. To explain these features and also the banded nature of the ore, Schwerin (5, p. 335) proposed the concept that the indicated volume shrinkage took place because of stoichimetric replacement of calcium carbonate by calcium fluoride. This was affirmed later by Currier (3, pp. 44, 45) who also implied that direct solution of limestone in excess of the amount of fluorspar deposited might be an additional cause for shrinkage. Schwerin made no specific reference to the subject, but Currier considered the prominent synclinal sags in the roofs over many deposits to be of structural origin (3, p. 41); he did not recognize that they might have resulted from volume contraction during the ore-forming process as herein postulated.

EVIDENCE OF VOLUME SHRINKAGE.

Evidence gained in recent years from study of extensive mine exposures and records of hundreds of borings not available to earlier investigators indicates clearly that volume shrinkage was a common and characteristic effect of mineralization. A net loss of rock volume during ore formation is indicated by measurable thinning of strata where they have been affected by ore solutions, sagging of strata overlying ore deposits with the formation of solution synclines, transection of the bedding of unreplaced limestone by the sloping margins of ore bodies, V-structures on large and small scale within deposits, breccias of roof-rock fragments cemented by fluorspar at the tops of deposits, and the presence of open cavities at the tops and margins of deposits, including extensive tabular open spaces between ore and roof. Data in support of this thesis are presented under three headings, namely evidence from structure maps and cross-sections, from statistics on formation thickness, and from the internal character of the deposits themselves.

Evidence from Structure Maps and Cross-Sections.—Synclines over many deposits are clearly revealed by structural contour maps based on drilling records. One of the most marked of these is shown in Figure 3 by means of contours that show the elevation of the Bethel-Renault contact. The syncline is underlain by mineralized rock in the top of the Renault formation within the area shown by shading, and is bordered by unmineralized ground. This structure has a known length, as illustrated, of 5400 feet, a width of 300 to 700 feet, and a depth of 10 to 40 feet. Some other structures in the district are longer and some are shorter, but in general they are less deep. In the barren areas adjoining these mineralized structures, subsurface contours disclose only gentle dips of uniform character such as that indicated on the right of the syncline in Figure 3.

That this syncline was formed as the result of local thinning of limestone strata in and adjacent to the mineralized zone is illustrated by the cross-section in Figure 4, which was drawn along the line of borings indicated in Figure 3. The borings at both ends of the section are in barren ground whereas the others show a greater or lesser degree of zinc and fluorspar mineralization as indicated, the greatest amount of mineralization being shown by boring No. 10. Above and below the zone most affected by mineralization the strata exhibit

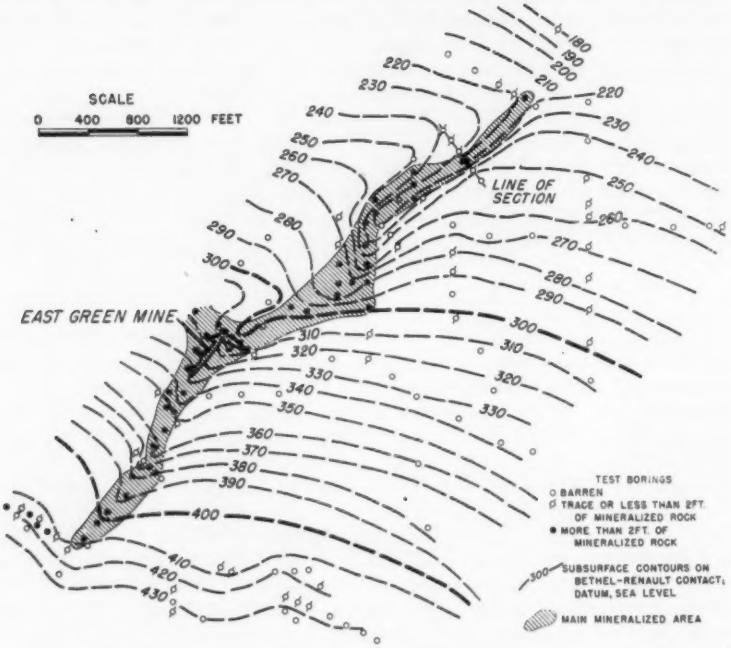

FIG. 3. Typical syncline associated with linear area of mineralization, as revealed by test-drilling.

a uniform slight dip from right to left, whereas within the area of mineralization they dip synclinally toward the center, as shown by their departure from the dashed lines which represent their postulated original position. The synclinal attitude is the result of thinning of the Fredonia, Levias, and Renault limestone formations. Because the thinning is localized in the area of ore formation, it is considered to be the consequence of volume shrinkage that attended the mineralizing process.

Evidence from Statistics on Formation Thickness.—A statistical study of the variation of the interval from the base of the Bethel sandstone to the top of the Fredonia limestone in barren and in mineralized ground shows that the

association of synclines and mineralized ground is a general characteristic of the district. Drill-records from all over the district were used in making the study, the results of which are shown in the three histograms on the left side of Figure 5. Each bar in the histograms records the number of borings in which the reference interval between the base of the Bethel sandstone and the top of the Fredonia limestone is a specified thickness.

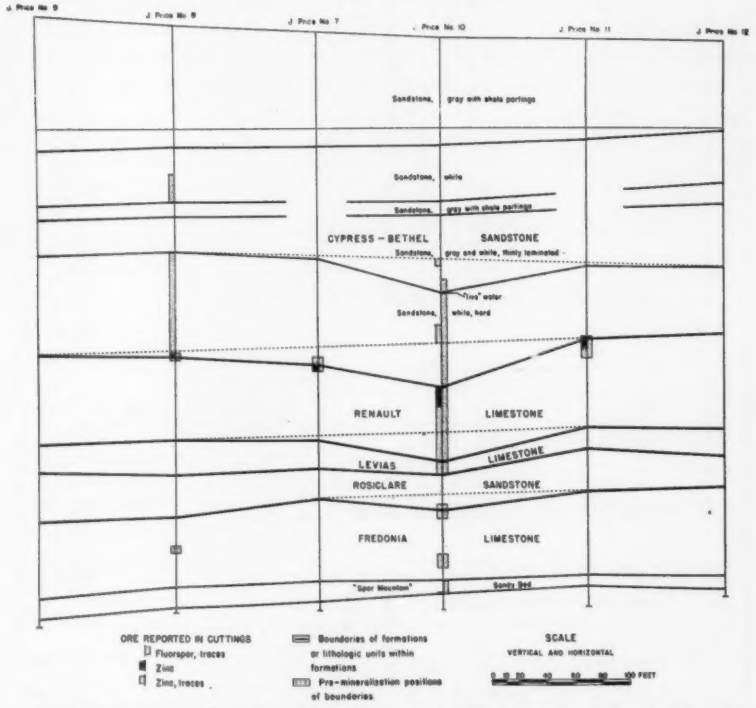

FIG. 4. Cross-section along line of borings indicated in Figure 3, showing that the syncline is restricted to beds affected by mineralization.

In the topmost histogram, representing a group of 383 borings in barren ground, the median thickness of the reference interval is 115 feet as indicated by the black bar. Forty-six percent of the borings had intervals less than, and 45 percent had intervals greater than, the median thickness. The middle histogram represents a group of 121 borings in which the Renault and/or Levias limestones, but not the underlying Fredonia limestone, have been strongly mineralized. In this group 86 percent of the intervals had thicknesses less than the median thickness in barren ground and 11 percent had greater thicknesses. The bottom histogram represents a group of 219 borings

in which strong mineralization has taken place in the Fredonia limestone, but not in the overlying Renault and Levias formations. Here 53 percent of the measured intervals are greater and 41 percent are less than the median value for barren ground.

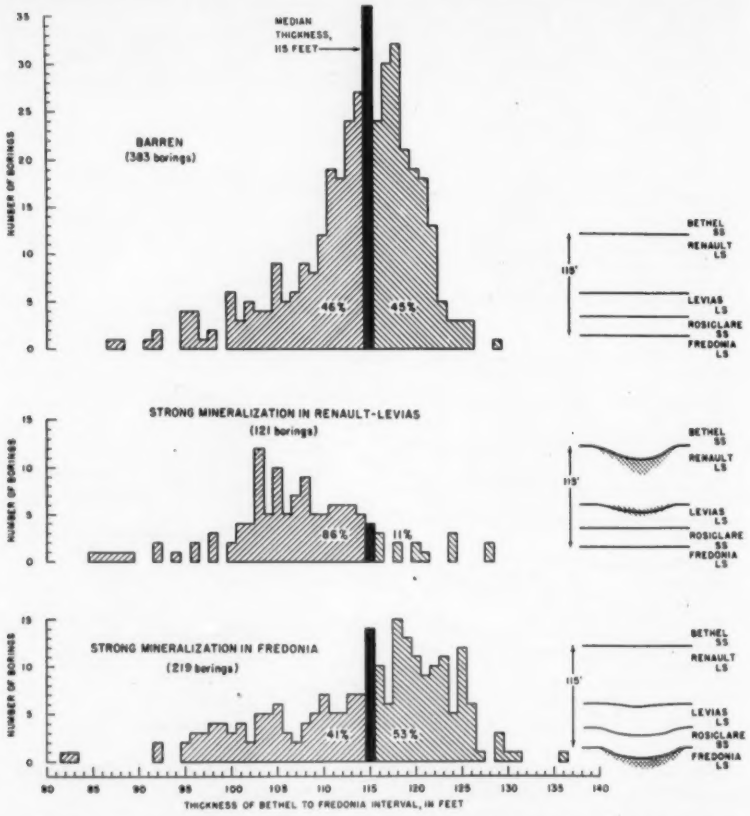

FIG. 5. Histograms and diagrams illustrating relation between thickness of interval from the base of the Bethel sandstone to the top of the Fredonia limestone in borings in barren and mineralized ground. Percentage figures refer to numbers of borings in which the reference interval is larger or smaller than its median thickness in barren ground. Cross-hatched areas in diagrams indicate stratigraphic position of mineralized strata.

The three diagrams to the right of the histograms show what has apparently happened in each case. The upper diagram shows the initial condition in barren ground where the reference interval is 115 feet. The middle diagram

shows mineralized ground in the top of the Renault and Levias limestones, where the consequent sagging of the strata gives rise to a reference interval shorter than in barren ground. The bottom diagram shows that the volume shrinkage and sagging occurred in the top of the Fredonia limestone along with mineral deposition at that level, and because the top of the Renault was unaffected and remained in its original position, the interval was lengthened to more than its original value.

Evidence from Internal Characteristics of the Deposits.—Numerous small-scale features of the deposits also confirm the idea of volume loss during mineralization, and afford an understanding of the mechanism involved.

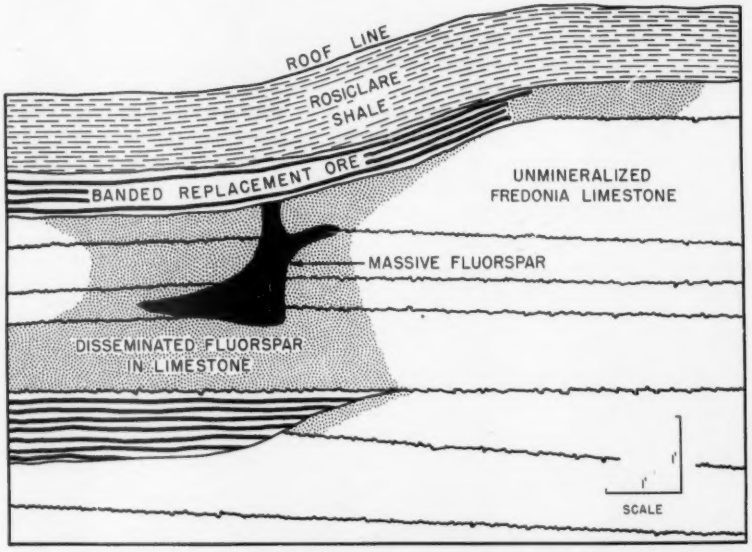

FIG. 6. Scale drawing of typical relations at the edge of a bedding-replacement ore body. The shaly caprock dips sharply at the edge of the deposit, in contrast to the nearby horizontal attitude of the underlying beds as shown by stylolitic bedding planes (irregular horizontal lines). Part of the topmost bed of limestone has been removed by solution which has allowed the overlying beds to sag.

Figure 6 is a scale drawing of the marginal portion of a particular ore body, but the relations are typical of many other deposits in the district. Of significance is the flat-lying character of the unmineralized Fredonia limestone, indicated by the horizontal stylolitic bedding planes, which contrasts with the sharp dip of the thin bed of banded replacement ore and the shale caprock at the edge of the deposit. The sharp dip is clearly the result of subsidence that followed the solution and removal of more than half of the thick limestone bed below the thin bed of ore. The same situation is shown in miniature in

Figure 7. The horizontal bedding of the limestone is apparent on the left above and below the hammer. The dark-colored V-shaped mass in the center, whose sloping margins sharply transect the limestone bedding, may be considered the equivalent of an ore body. The light-colored lenticular bodies within the V-shaped mass are barite which originally were part of a thin band at the base of the overlying limestone stratum, but which sagged down as limestone was dissolved and came to rest on a bed consisting of clay and small masses of soft, partially leached limestone, clearly a residue from the solution of the limestone. The material above the barite is a structureless, plastic, sandy red clay, similar to the surface residual clay of the region, that was brought by groundwater through crevices into the space left above the barite band. The overlying limestone could not sag into the space because of its rigidity and the short span left unsupported.

Figure 8 shows part of a mine pillar. The inward dipping slabs of partly or wholly replaced limestone beneath an essentially flat undisturbed roof indicate collapse brecciation following active local solution and removal of part of the original limestone. Similar structures are common at the tops of ore bodies, where fragments of the caprock spalled off into solution or subsidence openings and became cemented by massive fluorspar that was deposited around them. In portions of some ore bodies in the top beds of the Fredonia limestone, solution collapse has carried fragments of the overlying thin-bedded and shaly Rosiclare sandstone as much as 20 feet below their original level. These extreme cases occur typically in narrow linear zones that follow the courses of joint-like fractures which apparently allowed free circulation of the ore-bearing solutions, and consequently an extra-normal amount of solution of the limestone.

Figure 9 shows a portion of another mine pillar in which a 1-inch fine-grained band has split off from the base of a bed of banded replacement ore and slopes down into a body of light-colored massive fluorspar. This is evidence of the sagging of a rock layer into a former opening that was made by solution of limestone and subsequently filled with fluorspar. The same process is believed to account for the manner in which banded ore in some exposures dips inward and downward more or less symmetrically on the two sides of vertical veinlets of fluorspar, producing V-shaped structures like that shown in Figure 10. Massive fluorite, which appears dark in the photograph, fills the space next to the roof left open by the sagging above the V-structure. Bastin (1, pp. 47, 48) observed and prepared sketches of the same structures, including one W-shaped, but attributed their formation to rythmic banding produced

FIG. 7. Small structure illustrating relations present on a large scale in fluorite deposits. Dark-colored V-shaped mass is largely clay, in which lenticular masses of white barite are remnants of a band of barite formerly located at the top of the "V." Solution of limestone below the barite allowed the latter to sag into its present position. Photograph of adit wall.

FIG. 8. Steeply dipping slabs of mineralized rock below undisturbed roof imply collapse into a zone where mineralizing solutions removed much of the original limestone. Light-colored areas are mainly coarsely crystalline fluorspar. Photograph of mine pillar.

FIG. 7

FIG. 8

FIG. 9

FIG. 10

by diffusion of ore solutions outward from the central fractures, which was in line with his hypothesis that all the banded ore was the result of rythmic diffusion banding. The prevalence of solution and volume shrinkage effects herein described, as well as Currier's (3, pp. 36–39) generally more satisfactory explanations for the origin of the banded ore, tend to make Bastin's views less tenable. Probably most of the distortion of the lamination in ore beds, beyond that attributable to cross-bedding in the original limestone, may be explained as the result of solution and shrinkage during mineralization.

Still other evidence of solution shrinkage is afforded by the cavities lined with crystals and the masses of massive fluorite representing completely filled cavities which are abundant, especially at the tops and margins of many deposits, and by the open spaces from half an inch to a foot wide that in some places extend over hundreds of square feet between the base of the caprock and the top of the ore. These were voids formed by uncompensated loss in rock volume.

MECHANISM RESPONSIBLE FOR VOLUME SHRINKAGE.

The mechanism responsible for the foregoing phenomena appears to be a combination of volume reduction owing to stoichimetric replacement of the calcite in limestone by denser fluorite, and of volume loss due to actual removal of limestone by the action of solvent mineralizing fluids.

Theoretically the volume reduction from stoichimetric replacement could amount to as much as 33 percent, for 100 grams of calcium made into fluorite occupies only two-thirds of the volume required by 100 grams of calcium made into calcite. The properties of the limestone and the ore produced from it indicate that this optimum shrinkage rarely occurred except in local situations, for none of the limestone is pure, replacement is rarely if ever complete except in small areas, and the ore is practically always more porous than the original limestone.

Removal of limestone through solution by the ore-forming fluids may have been a large or small contributor to the total loss in volume. Large effects are easily recognized, such as situations in which fragments of the caprock are found 20 feet or more below their original position, or limestone beds are visibly truncated, but much material may have been lost from a limestone bed without the evidence being clearly preserved in the resulting bed of ore. In some places strong synclinal effects are present even though no great amount of fluorspar has been formed. In such places a large share of the volume loss must be attributed solely to solution of limestone.

FIG. 9. Layers of dark-colored ore sloping downward into a mass of light-colored coarse fluorite indicate collapse of rock layers into former opening now filled with mineral. Scale is shown by mark of drill in banded ore at upper left. Photograph of mine pillar.

FIG. 10. Structure at upper left is a typical "V" centering about a vertical fissure. Such structures are believed to have formed by the symmetrical sagging of numerous thin rock layers into a zone of active solution along the central fissure. Note the two dark-colored areas on either side of the fissure at the top of the "V," which are crystal-lined cavities formed by the sagging of the layers below. Photograph of wall of mine.

CONCLUSION.

It is concluded that the following chronological events explain the phenomena described and indicate the probable relations of structure to the formation of the Cave in Rock deposits:

1. Major normal faulting along the Peters Creek fault zone.
2. Formation of northeast and northwest sets of fractures and minor faults, possibly coincidental with movement along the Peters Creek fault zone, perhaps later.
3. Rise of moderate-temperature mineralizing solutions from depth, probably along the Peters Creek fault.
4. Spreading out of solutions from the Peters Creek fault into and upward along certain of the sets of supplemental fractures and minor faults which were probably connected with it. Possibly solutions rose along only a few main channelways and then spread laterally to a considerable extent.
5. Replacement and chemical solution of limestone strata which were more readily attacked than others by reason of greater porosity or larger pores, or because they were more shattered in the preceding period of fracturing associated with the development of the Peters Creek fault. Probably the deposits formed wherever further upward or lateral movement of solutions was restricted by lack of suitable continuous channel-ways.
6. In the mineralizing process a denser mineral was substituted for one less dense, and more material was removed than was added by the solutions, resulting in a net loss in rock volume at the sites of mineral deposition. Subsidence of the overlying beds accompanied and followed this process, producing solution synclines.

ILLINOIS STATE GEOLOGICAL SURVEY,
URBANA ILL.,
July 11, 1949.

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4. Weller, J. M., Grogan, Robert M., and Tippie, F. E., Geology of the southern Illinois fluorspar deposits: Illinois Geol. Survey, unpublished manuscript.
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ELECTRON MICROSCOPY OF COAL.[1]

J. T. McCartney.

ABSTRACT.

A technique for preparing specimens of coal for electron microscopy has been developed. The usual thin-section or peel methods of coal petrography are inadequate. The coal specimens are etched in chromic acid-sulfuric acid and the structures thus revealed are reproduced in extremely thin replica films of Formvar (polyvinyl formal). Electron micrographs of microspores in attrital coal and cell structures in anthraxylon are illustrated. Details are revealed that are beyond the limits of the optical microscope.

INTRODUCTION.

The possibility of adapting the electron microscope to studies of coal petrography and coal paleobotany has been investigated intermittently for several years at the Pittsburgh Station of the Bureau of Mines, U. S. Department of the Interior. Because of the limitations of this instrument in the types of specimens that can be accommodated, the usual techniques of coal petrography have not been adequate. Thin sections of coal seldom are ground thinner than 5 to 10 microns, whereas the thickness of specimen desired for the electron microscope is not over 1 micron, and preferably nearer 0.1 micron. Furthermore, there is some doubt as to the preservation and recognition of the original structures in such a thin section if it could be prepared. Studies of bulk specimens by reflection methods are as yet impractical. The so-called peel techniques [2] give specimens that approach the desired conditions, but these are still too thick for any profitable studies.

SPECIMEN TECHNIQUES.

Of the various techniques developed for electron microscopy, the most promising for coal studies are the replica methods. There are many variations of these, but all have as their final product a very thin film of resin, silica, or metal in which the contours and fine details of the original specimen surface are reproduced. These are imaged in the electron microscope by the differential scattering of the electron beam caused by differences in thickness of various areas of the replica film. A number of these methods were applied to coal with little success. Difficulties were encountered in separating the replicas from the coal and in obtaining faithful reproduction of recognizable structure in the final film. However, a suggestion in the literature [3] led to the development of a technique that proved very effective for coal.

[1] Published with permission of the Director, U. S. Bureau of Mines.

[2] Darrah, William C., The peel method in paleobotany: Botanical Museum Leaflets, Harvard University, vol. 4, pp. 69–83, 1936.

[3] Cosslett, V. E., Recent advances in electron microscopy in the United Kingdom: Research, vol. 1, pp. 293–304, 1948.

The coal specimens (about ¾-inch cubes) are first polished by the usual polishing methods, then etched for a short period (10 seconds to a few minutes depending on the rank of the coal) in a chromic acid-sulfuric acid

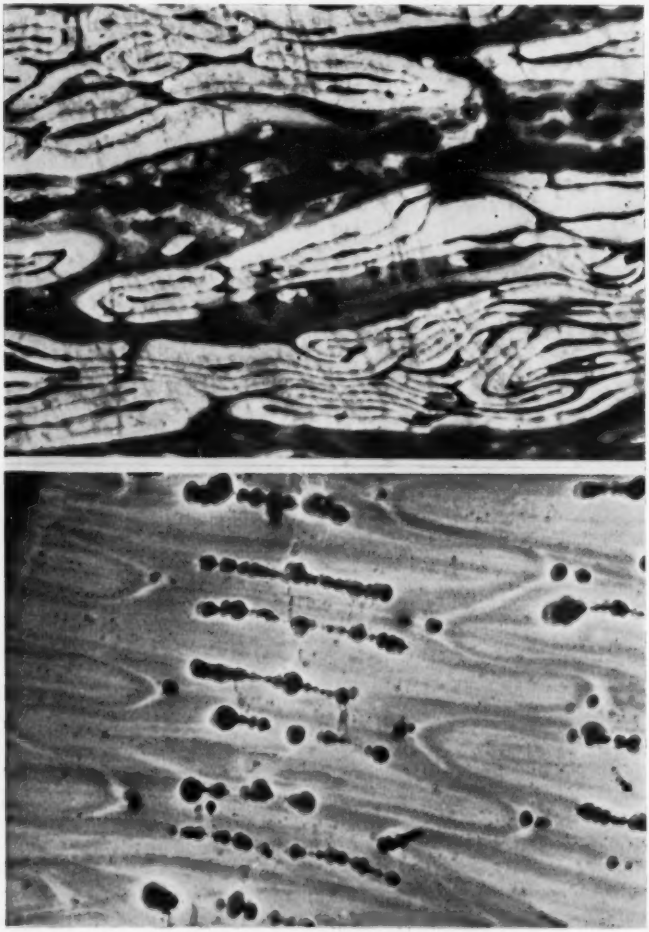

FIG. 1. Electron micrograph of a Formvar replica of micro-spores in attrital coal. × 4500.

FIG. 2. Electron micrograph of a Formvar replica of cell structure in anthraxylon. × 2000.

etchant.[4] After washing and drying in a stream of filtered air, they are dipped in a 0.7-percent solution of Formvar (polyvinyl formal) in ethylene dichloride. After the solvent has evaporated, a 10-percent solution of nitrocellulose in butyl acetate is spread over the surface. After drying, the double film of Formvar and nitrocellulose is loosened at one edge with a razor blade and then peeled from the surface. The film may tear during stripping, but unless the specimen is etched too deeply, a sizable area of film is usually obtained. This double film is then observed under an optical microscope, and ⅛-inch discs of 200-mesh screen, used for support of electron microscope specimens, are placed over areas showing good structure. These are fastened to the Formvar side of the film with Scotch tape. The tape with the film and screens attached is placed in amyl acetate, a solvent for nitrocellulose. After an hour or so, the tape is removed from the solvent, and the screens are picked off the softened adhesive with tweezers and placed in a second bath of amyl acetate to dissolve any remaining traces of nitrocellulose film and adhesive from the Scotch tape. Containing now only the Formvar replica, about 0.1 micron thick, the screens are then removed and dried and are ready for observation in the electron microscope. It may be desirable to investigate the possible enhancement of contrast and detail in these replicas by the metal-shadowing technique,[5] but so far this has not appeared necessary.

SAMPLE ELECTRON MICROGRAPHS.

Figures 1 and 2 show sample electron micrographs of coal structures reproduced in such replicas. Figure 1 shows a replica of attrital coal in which the prominent entities are microspores. The spores appear lighter in the micrograph because, being more resistant to etching, they project above the surrounding material and the replica film is thinner over these areas. Only the compressed outer coats of the original spores remain in the coal, the dark lines marking separation of the opposite sides. It is doubtful whether many of these details of compression and folding would be clearly shown with an optical microscope. Figure 2 shows preserved cell structure in anthraxylon. The light, wavy lines represent the middle lamellae of the cells. The darker areas surrounding these show where the less-resistant parts of the cell walls were etched out. The lighter larger areas represent the cell lumens, which probably were filled with some resistant material. The significance of the rows of dark spots is not as yet known, although they probably represent material that has adhered to the replica film.

These micrographs are presented to illustrate the results that can be obtained on coal with the electron microscope. It is hoped that studies of this nature will reveal more clearly some of the finer details of coal structure that are not as yet fully understood.

[4] Seyler, C. A., The microscopical examination of coal: Dept. Sci. and Ind. Research, 67 pp., London, 1929.

[5] Williams, R. C., and Wyckoff, R. W. G., Applications of metallic shadow casting to microscopy: Jour. App. Phys., vol. 17, pp. 23–33, 1946.

ACKNOWLEDGMENTS.

The author wishes to thank the following members of the staff of the Coal Constitution and Miscellaneous Analysis Section, Central Experiment Station, Bureau of Mines, Pittsburgh, Pa.: W. A. Selvig, supervising chemist, and B. C. Parks, coal technologist, for helpful suggestions in this work; and H. J. O'Donnell, scientific aid, for selecting specimens showing definite microstructure of coal.

COAL CONSTITUTION AND MISCELLANEOUS ANALYSIS SECTION,
CENTRAL EXPERIMENT STATION,
U. S. BUREAU OF MINES,
PITTSBURGH 13, PA.,
June 17, 1949.

A HYPOTHESIS ON THE ORIGIN OF A LIMONITIC LAYER IN BEDS OF EOCENE AGE IN FAYETTE COUNTY, TENNESSEE.[1]

ROBERT SCHNEIDER.

MANY layers of limonite together with limonitic conglomerate or sandstone of differing thickness and lateral extent have been observed in western Tennessee at the base of Pleistocene and Pliocene, Eocene, and Cretaceous sands or gravels which immediately overlie impervious layers of clay or sandy clay. They are considered to be the result of the accumulation of iron oxide which precipitated from descending ground waters. The lithologic sequence in which limonitic layers underlie clay and overlie sand or gravel probably occurs much less frequently than the above. Monroe, Conant, and Eargle [2] have described two sections of the Upper Cretaceous in western Alabama in which limonitic sandstone layers are overlain by beds of clay or clayey sand and underlain by sand.

V. T. Stringfield, P. E. LaMoreaux, and H. E. LeGrand,[3] geologists, U. S. Geological Survey, and others, have noted similar limonitic layers in the same vertical lithologic sequence in the Coastal Plain of western and southern Alabama and other parts of the Coastal Plain.

The limonitic deposits described above are usually in irregular plates and sheets and occasionally also in the form of tubes. In any one exposure the thickness of the limonitic layer varies as much as 8 inches. Because of the variability of form and thickness of the layers it is believed that they could have been formed by ground waters that had seeped downward through the overlying clay layers.

The ocurrence of a uniformly thin, single layer of limonitic sandstone at the contact between a layer of clay and a bed of sand under the clay seems interesting and different enough to warrant some speculation as to its origin.

Extensive gullying south of State Highway 57, about 2.4 miles west of the center of La Grange and 6.5 miles east of Moscow, Fayette County, Tennessee, has exposed the following section, described by G. I. Whitlatch [4] and given here with some modifications by the writer:

	Thickness (feet)
4. Sand, dark-brown to red, medium-grained. Grains coated and weakly cemented with iron oxide.	3–18
3. Clay, bluish gray and white, mottled with pink, silty to sandy.	0.5–10
2. Sandstone, limonitic, fine-grained, hard, in northern part of exposure only.	0.01
1. Sand, streaked and mottled yellowish-tan, brown, and orange, micaceous, fine- to medium-grained, cross-bedded, unconsolidated.	28 +

[1] Published by permission of the Director of the U. S. Geological Survey.

[2] Monroe, W. H., Conant, L. C., and Eargle, D. H., Pre-Selma Upper Cretaceous stratigraphy of western Alabama: Am. Assoc. Petroleum Geologists Bull., vol. 30, no. 2, pp. 187–212, Feb. 1946.

[3] Personal communications.

[4] Whitlatch, G. I., The clays of West Tennessee: Tennessee Div. Geology Bull. 49, p. 295, 1940.

According to Whitlatch, the lowermost 15 feet of stratum 1 may be the uppermost part of the Holly Springs formation [5] (middle part of the Wilcox group). The beds above are presumed to be in the Grenada formation (upper part of the Wilcox group). These correlations probably were based on the mapping of Roberts and Collins.[6]

The Eocene stratigraphy as interpreted by Roberts and Collins was based on a subdivision of the Eocene of Mississippi by Lowe.[7]

According to the most recent geologic map of Mississippi,[8] part of the area which was mapped earlier as Wilcox (lower Eocene) may actually belong, in part at least, to the Claiborne group (middle Eocene).

The age of the beds has no direct bearing on the origin of the limonitic layer under discussion because it is a secondary feature. Consequently, for the purposes of identification only, the beds have merely been assigned to the Eocene series.

Stratum 3 actually consists of several more or less distinct beds of silty and sandy clay which are 1 to 2 feet thick. The contact between stratum 3 and stratum 4 is very irregular, thus accounting for the variable thickness of stratum 3.

The sand of stratum 1 is locally cross-bedded up to angles of 30° or more. In several of the cross-bedded sections, rounded grayish-white pebbles of clay up to an inch in diameter were found.

The contact betwen stratum 1 and stratum 3 (disregarding stratum 2) is relatively even and distinct. The upper few feet of the sand in stratum 1 is speckled with tiny white clay fragments. Eight or ten inches of the sand immediately under the contact contains numerous thin clay laminae and lenses which are up to an eighth of an inch thick.

In most of the northern part of the exposure a hard layer of limonitic sandstone up to one-eighth of an inch thick (stratum 2) marks the contact between stratum 1 and stratum 3. Fragments of the limonitic sandstone layer cap the sand where the clay has been eroded away.

Regionally, the Eocene sediments of western Tennessee are on the east flank of the Mississippi Embayment syncline. Well-developed artesian conditions exist in the Embayment, and it is safe to assume that in the past the same conditions prevailed, except that the sections of the formations which are now exposed were once buried under other sediments. Sandy formations, that now contain water under water-table conditions in the areas where they crop out, may once have contained water under artesian pressure in the same places.

The above conditions are postulated for the section under consideration. Stratum 3 was the upper confining layer for the water in stratum 1. Erosion and weathering of stratum 3 caused the formation of many minute holes, cracks and crevices, producing the same effect that would have been achieved by drill-

[5] The U. S. Geological Survey regards the Holly Springs as a member of the Tallahatta formation.

[6] Roberts, J. K., and Collins, R. L., The Tertiary of West Tennessee: Am. Jour. Sci., 5th ser., vol. 12, pp. 235–243, 1926.

[7] Lowe, E. N., Preliminary report on iron ores of Mississippi: Mississippi Geol. Survey Bull. 10, 1913.

[8] Geologic map of Mississippi, Mississippi Geol. Soc., 1945.

ing a well through the clay; that is, an avenue of escape was provided for the water under pressure. Instead of a well, however, there were numerous tiny openings in the confining layer through which water from stratum 1 could seep upward.

As the clay layer became thin and leaky, it is possible that solid ferrous carbonate was precipitated from the water, owing to the loss in head and resulting release of carbon dioxide as the water moved through the small openings in the clay.

Harder [9] and Eckel [10] have stated that waters containing an excess of carbon dioxide will retain iron in solution as ferrous bicarbonate if it is not oxidized. Wherever conditions are such that the waters can lose carbon dioxide, ferrous carbonate, or siderite, may be precipitated. The small openings in the clay immediately above the sand probably became clogged with the precipitate, and eventually, as more of the overlying material was stripped off by erosion, the siderite was oxidized and hydrated to form the limonite of stratum 2.

Additional field work in this area has not revealed that the limonitic layer under consideration extends for any appreciable distance laterally. However, the conditions suitable to the formation of the layer, as suggested above, may have existed only locally. The relative thinness of the limonitic layer could be due to (1) subsequent deposition of sediments that effectively thickened the upper confining layer of the aquifer and sealed the leaks in it; or (2) sealing of the openings by the precipitate, stopping the upward movement of water through the confining bed.

The mode of origin and nature of the distribution of iron in solution in ground water are imperfectly known. Available analyses of water from Eocene sands in western Tennessee indicate a range from zero to about 2.80 parts per million of dissolved iron. In several places it has been found necessary to aerate ground water and filter out the precipitated iron in order to prevent the staining of fixtures in which the water is used. The entire subject of the presence of iron in ground water is one that requires more intensive research by ground-water geologists, engineers, and chemists.

It is realized that probably more data should be accumulated before the origin of limonitic layers similar to that described above can be determined with any degree of certainty. This hypothesis is presented, however, with the view in mind that it will encourage discussion.

U. S. GEOLOGICAL SURVEY,
GROUND WATER BRANCH,
MEMPHIS, TENN.
June 13, 1949.

[9] Harder, E. C., Iron-depositing bacteria and their geologic relations: U. S. Geol. Survey Prof. Paper 113, pp. 71–72, 1919.

[10] Eckel, E. B., The brown iron ores of eastern Texas: U. S. Geol. Survey Bull. 902, p. 46, 1938.

DISCUSSION AND COMMUNICATIONS

LABORATORY TESTING OF "PNEUMATOLYTIC" DEPOSITS.

Sir: In the course of testing the temperature of formation of ore deposits, making use of the degree of filling of liquid inclusions, graduate students of this department and I have found a considerable number of discrepancies between the measured values and the estimates made in the past. We hope to publish the results in the form of formal papers as soon as each project is completed, but in one case I wish to present preliminary results, with the hope that the readers of this journal will aid in the study.

We have begun a test of the postulated pneumatolytic origin of certain ore deposits, the test being merely a measurement of the degree of filling of the fluid inclusions in the minerals. If the inclusions are nearly voids, then the transporting agents were of low density, and conversely.

The term "pneumatolysis" as a process of ore deposition has become somewhat less used in the last two decades, but it apparently is still employed, especially on the engineering and teaching level of the science. Modern text books of economic geology are not as positive as the following excerpt from "Ore Deposits" by Beyschlag, Vogt, and Krusch (Vol. 1, 1914): "One entire class of deposit, that of the tin lodes, owes its existence entirely to the action of these gases or vapors either between themselves or upon the rocks with which they come in contact." For example, in "Economic Mineral Deposits," by Bateman (1942), this statement is made: "In the past it has generally been considered that contact-metamorphic ore deposits have been formed from gaseous emanations. Field evidence, however, indicates that if deposits have been so formed liquid emanations have operated in the later phases of their formation."

It is surprising that the ubiquitous liquid inclusions of ore and gangue minerals have not been used either to establish or contradict the oft-postulated pneumatolytic origin of certain deposits, for if the small trapped samples of the solvent fluid can be seen to be of low density, then the term can be retained, but if of high density, then another term such as "hydrothermal" must be used. It will be recalled that in several deposits, Lindgren used liquid inclusions to substantiate his contention that pneumatolysis was unlikely.

The tin deposits of Cornwall were chosen as a first test of the method. A few representative samples available in teaching collections were studied to obtain the qualitative data. One sample from St. Austell, Cornwall (Dept. Geol. Sci. No. A 1693) consisted of a vuggy intergrowth of tourmaline, cassiterite, and quartz. The temperatures of filling of the liquid inclusions by the liquid phase (using the decrepitation method) were 345°, 345°, and 329° C respectively. A coarse intergrowth of quartz, wolframite, and chalcopyrite from the South Crofty Mine, Cornwall (Dept. Geol. Sci. Nos. 8102 and 8123),

gave filling temperatures of 293° for the quartz, and 242° for the wolframite. An intergrowth of coarse chalcopyrite and quartz from the Tincroft Mine, Cornwall (Dept. Geol. Sci. No. 8090) gave a filling temperature of 261° C for the chalcopyrite. Under the microscope, the liquid inclusions in the quartz from the three localities were found to be of the normal type, consisting of a gas bubble in a larger amount of liquid. Therefore the deposits were not formed by pneumatolysis, but by the usual hydrothermal liquids.

The conversion of the liquid inclusion filling temperatures to temperatures of deposition, depends upon the pressure during deposition. There are several facts which suggest that the depth during deposition of the Cornish ores was not great, such as the low grade of regional metamorphism and the rapid vertical zoning in the deposits (see Davison, E. H. in ECON. GEOL. Vol. 22, pp. 475–479, 1927). Making the reasonable assumption that the pressure was equivalent to two miles of rock load, the decrepitation results can be converted to the following temperatures of deposition:

Wolframite (South Crofty)	265° C
Chalcopyrite (Tincroft)	280° C
Quartz (South Crofty)	345° C
Quartz (St. Austell)	370° C
Cassiterite (St. Austell)	390° C
Tourmaline (St. Austell)	390° C

Having concluded that the Cornish tin deposits are not pneumatolytic in origin, the question arises: are there *any* pneumatolytic ore deposits? I propose to test any samples of possible pneumatolytic deposits sent to me by universities, mining corporations or individuals, with this question in mind, the results to be published in this journal.

F. GORDON SMITH.

DEPARTMENT OF GEOLOGICAL SCIENCES,
UNIVERSITY OF TORONTO,
TORONTO, ONTARIO,
May 19, 1949.

ORE AND GRANITIZATION.

Sir: While compiling some notes for submission as a discussion on Mr. C. J. Sullivan's paper,[1] I became aware of a similar discussion being prepared by Dr. A. B. Edwards and Mr. A. J. Gaskin. A draft of this last discussion has been made available to me by the authors. As I am in general agreement with the views of Dr. Edwards and Mr. Gaskin, my further remarks will be confined to brief notes on one or two additional points concerning Mr. Sullivan's paper.

Some of the production statistics quoted by Sullivan are open to criticism. It will suffice to quote only the Australian production of copper (p. 476). Speaking of the calendar year 1945, he states: "Less important production has come from the Paleozoic areas of Australia (24,000 tons)." The facts are that the Mt. Isa production of 11,763 tons, and some of the remainder of

[1] ECON. GEOL., vol. 43, pp. 471–498, 1948.

the Queensland production, came not from Paleozoic rocks but from the Precambrian.

Even if we grant Sullivan's presentation of the statistics as representing the true facts, elementary statistical analysis shows that the hypothecated relationship between metals and geological age is not statistically significant.

Sullivan refers on pages 478 and 492 to the Broken Hill deposits in New South Wales. In the former place, he states: "There is no doubt, of course, that many deposits including the Broken Hill lode are closely associated with granite." In the second place, he appeals to the extensive published and unpublished geological work at Broken Hill, and to his own visit of one week, to support the view that "it appears not unlikely that most of the so-called igneous rocks, including the basic ones in the vicinity of the ore deposits, have been formed by the metasomatic alteration of sediments and that, in effect, the ore body occurs within the femic metasomatic aureole of a granite cupola formed at some depth by replacement of a tightly compressed anticline." Mr. Sullivan may have arrived at this conclusion on his visit, but the published and unpublished intensive work of geologists (after years of field work) do not support it. Both the visible granitic rock types and the basic rock types in the neighborhood of the Broken Hill lode are sills which were injected before, or during the early stages of, a period of intense folding which itself preceded the deposition of the lode. It has certainly been suggested that some of the granitic sills may have been formed in part at least by granitization, but the suggestion has not been substantiated, and in any case it need not have been related to the formation of the ore in any way. There is no basis whatever for considering the basic sills as other than metamorphosed basic rocks. The undoubted association of early pegmatite with Broken Hill ore deposition is the only direct evidence of association of the ore deposit with granitic rocks.

I am unconvinced by Sullivan's contention that metals are concentrated into ore deposits only when incompatibilities exist between the ionic radius of the metal and the ionic radii of the cations of the parent igneous rocks. Thus, he states—"In the presence of abundant ferro-magnesian minerals, the large scale concentration of these elements (tin, etc.) may be practically impossible because of the similar ionic radii of iron (Fe^{2+},0.78) and magnesium (Mg^{2+},0.75) to those of the elements (tin, etc.) under discussion, and because of the relatively low valency of iron and magnesium." Using Sullivan's own figures of 0.96 percent substitution of tin oxide in spinel, and 1.37 percent combined iron and magnesium for average Precambrian granite, it seems fair to conclude that the granite could absorb 0.00013 tons of tin oxide per ton of rock. That is, a mass of 1,300 tons of tin oxide, in itself a nice oreshoot, could be absorbed by a cube of granite about 100 yards on edge, which is not much granite. Even if all the relevant figures are altered by several degrees of magnitude, it is a wonder that any tin ore was ever concentrated if Sullivan's hypothesis were the main concentrating control. Similarly, since Sullivan states (p. 486) that lead is likely to substitute for potassium, the behavior of lead in leaving any host igneous rock must be considered as unnatural.

I am familiar with only the two Australian examples among the five quoted by Sullivan on page 478 to illustrate lead deposits which are closely associated

with "volcanic" rocks. In the case of Captains Flat, neither the reference quoted by Sullivan nor my own later work give any support to the view that the porphyry is other than a sill injected prior to folding. Ore deposition took place subsequently to folding. At Read-Rosebery in Tasmania, the present-day view is similar to that mentioned for Captains Flat, although contrary views have been expressed in the past.

M. D. GARRETTY.

NORTH BROKEN HILL LIMITED,
MELBOURNE, AUSTRALIA,
July 5, 1949.

REVIEWS

Géologie des Gîtes Minéraux. By E. RAGUIN. Pp. 641; figs. 145; numerous tables. Masson & Cie., Paris, 1949. Price, 1650 frcs.

This second edition has been considerably revised. It develops more the study of various categories of mineral deposits, omitting the chapters on geological maps, applied geophysics and reflecting microscope for which the interested reader may refer to more specialized books. Yet the general outlay has been preserved.

The book is divided into an Introduction, Object and Methods of Geology as Applied to Mineral Deposits and Classification of the Mineral Deposits, and twenty-four chapters as follows: Underground Water; Thermomineral Springs; Igneous Deposits; Hydrothermal Deposits; Deposits by Surficial Waters; Sedimentary Deposits; Diamonds and Precious Stones; Mineral Combustibles; Petroleum; Calcium Phosphates; Lacustrian Deposits; Substances Based on Lithophile Elements; Magnesium; Radioactive Substances and Rare Earths; Tin, Tungsten and Molybdenum; Graphite, Titanium and Vanadium; Manganese; Platinum, Chrome, Nickel and Cobalt; Iron; Sulphur, Pyrite, Selenium, Tellurium, Arsenic, Antimony and Bismuth; Copper; Zinc, Lead and Cadmium; Silver and Mercury; Gold.

Each chapter deals with uses, production, metallogeny, and distribution by country or region. Where there are various types of deposits for one substance, each is discussed separately with its distribution. The author has found that treating the subject matter substance by substance, instead of by types of deposits of varied substances, was more appropriate as the book is a treatise of applied geology rather than theoretic metallogeny, and thus shows the importance of each substance and its world distribution.

Changes have been made in the important question of metallogenetic classification. Impregnation deposits have been linked to hydrothermal deposits. Pneumatolytic deposits have been more individualized, taking into account Fersman theory on pneumatolytes. Substitution deposits with uncertain affinities have been related to telethermal deposits, according to modern trends. Schneiderhohn's deposits of submarine volcanic exhalation have been precised. New developments have been added in the description of the principal coal deposits of the world, on Bolivian tin veins and Moroccan lead deposits. Whenever new material was obtained on more recent deposits, whole paragraphs were revised.

The illustrations were all hand drawn by the author and very clear. At the end of each chapter is a short bibliography of works referred to or for more detailed reading on each particular subject, which shows the great amount of research done. Statistics for production have been taken from the *Minerals Yearbook*, except those for France and French possessions, which were taken from the *Ministère de la Production Industrielle*. Unfortunately the statistics are brought up only to 1945, which is nevertheless informative as it gives the uncertain production during the war.

The book is well presented, clearly and agreeably written, and although not quite up to date, should be valuable for a general study of mineral deposits.

M. L. MIGNONE.

The Domestic Mining Industry of the United States in World War II. By JOHN D. MORGAN, JR. Pp. 500 (mimeographed); figs. 74; charts 30. National Security Resources Board. U. S. Government Printing Office, Washington, D. C., 1949.

The purpose of this bulky report is to bring together considerable of the available information regarding what happened about metals and minerals during World War II and thereby make it available for present and future planning. It is hoped that by this means mistakes of World War II may not be repeated in future planning. It is an ambitious doctorate dissertation and the author has dipped widely in government documents and files.

After an introduction on the historical relationship between wars and the mineral industry, the author presents a diplomatic and military history of World War II, the sources of U. S. mineral supply from 1938–1946, the Federal agencies involved, the man-power problem, and equipment and supply problems. The individual minerals are then discussed followed by a treatment of transportation, underground facilities, supplying the energy, the relation between Federal and State Governments in mineral policies, and stockpiles. A Conclusions and Recommendations chapter gives suggestions for future mineral policies and coordination. Appendices include the major federal directives regulating mining and a chronological review of the major diplomatic and military events of World War II. Much statistical matter is included.

It is suggested that there be a Federal Mineral Director with State Mineral Directors under him who would have absolute authority over the mines, their equipment, and their personnel in each State.

The great mass of data in this report will unquestionably be useful in formulating plans and policies for the mobilization of mineral resources for national defense.

Lo Stagno. By ELISEO BONETTI. Pp. 111. Trieste University, 1948.

The book starts with several pages on the history and development of tin through the ages and in the different countries, continuing with its industrial applications and mineralogy. The other sections are: the development of world production, geographical distribution of the production and commercial course of tin. The section dealing with the geographical distribution is divided into continents, then subdivided into the main tin areas. More emphasis is put on production and reserves than on the geology of tin itself. The references that accompany the text and the bibliography at the end of the book show that this study is not up to date, as most of the references are prior to 1941. However, an additional bibliography compiled for the statistics is more recent, but many figures are missing. Since the study stops before the war it shows that Great Britain, with its Dominions and Colonies, controlled the world production of tin, and also the United States' deficiency in tin at the beginning of the war.

M. L. MIGNONE

Oil Fields in North America. By W. A. VER WIEBE. Pp. 251; figs. 109; tbls. 63. Edwards Brothers, Inc., Ann Arbor, Michigan, 1949. Price, $6.00.

This $8\frac{1}{2} \times 11$ inch volume contains a description of every oil and gas area in the United States, Canada, Alaska, and Mexico. It gives their structure, stratigraphy, producing zones, traps, and statistics. There are maps and drawings showing cross-sections, facies changes, contours, reef characteristics and correla-

tions. There are tables of stratigraphic sequences, oil pools, and production. In fact, all information desired about any oil area in North America is succinctly compiled. It is not philosophic, it is informational.

Landscape, as Developed by the Processes of Normal Erosion, 2nd Edit. By C. A. COTTON. Pp. 509; figs. 375. John Wiley & Sons, New York, June 1949. Price, $10.00.

Those who have been familiar with Professor Cotton's first edition of this book will be glad to see it in an enlarged and rewritten form and with many new illustrations, some of which are bled photos. The new addition joins with *Climatic Accidents in Landscape-Making* (1942) and *Volcanoes as Landscape Forms* (1944) in making a notable set of books on geomorphology.

The present edition retains the form of its predecessor in dealing with the various processes operating on the surface of the earth and the land forms that result therefrom.

BOOKS RECEIVED.

M. L. MIGNONE.

U. S. Geological Survey—Washington, D. C., 1948–1949.

Bull. 956. Geology and Ore Deposits of the Libby Quadrangle, Montana. RUSSELL GIBSON, with sections on Glaciation by W. C. ALDEN, and Physiography by J. T. PARDEE. Pp. 131; pls. 11; figs. 7. *Moderately productive gold-bearing veins; one mainly quartz with small quantities of sulfides; description of several mines and prospects.*

Bull. 958. Bibliography of North American Geology, 1946 and 1947. EMMA MERTINS THOM, MARJORIE HOOKER AND RUTH REECE DUNAVEN. Pp. 658. Price, $1.50. *Latest and very useful addition to the series.*

Bull. 966–A. Geophysical Abstracts 136, January–March 1949. V. L. SKITSKY AND S. T. VESSELOWSKY. Pp. 93. *Contains abstracts nos. 10737 to 11001.*

Water Supply Papers.

1023–1027. Water Levels and Artesian Pressure in Observation Wells in the United States in 1945. Under the direction of C. G. PAULSEN. **Pt. 1. Northeastern States.** Pp. 373; figs. 22; numerous tables. **Pt. 2. Southeastern States.** Pp. 244; figs. 13; numerous tables. **Pt. 3, North-Central States.** Pp. 260; figs. 6; numerous tables. **Pt. 4. South-Central States.** Pp. 180; figs. 11; numerous tables. **Pt. 5. Northwestern States.** Pp. 244; figs. 4; numerous tables.

1077. Gaging-Station Records in the Missouri River Basin. B. R. COLBY AND R. E. OLTMAN. Pp. 219; figs. 10; tlbs. 3; chart 1.

1080. Floods of May–June 1948 in Columbia River Basin, with a Section on Magnitude and Frequency of Floods. Under the direction of C. G. PAULSEN; S. E. RANTZ, AND H. C. RIGGS. Pp. 476; pls. 12; figs. 27; tbls. 4. *Greatest flood in the basin since 1894.*

European Recovery Program—Nonferrous Metals. ECONOMIC COOPERATION ADMINISTRATION. Pp. 16; tbls. 5; 13 appendix tables. U. S. Government Printing Office, Washington, D. C., March 1949. *World position in 1948; future production outlook in 11 nonferrous metals.*

European Recovery Program—Iron and Steel Commodity Study. ECONOMIC COOPERATION ADMINISTRATION. Pp. 64; 22 appendix tables. U. S. Government Printing Office, Washington, D. C., March 1949. *Commodity and investment program; iron and steel production, consumption and trade in general and in 10 European countries.*

Atomic Energy and the Life Sciences. ATOMIC ENERGY COMMISSION. Pp. 203; 22 photos. U. S. Government Printing Office, Washington, D. C., July 1949. Price, 45 cents. *Major developments in Atomic Energy Programs; biology and medicine; particle accelerators; research in metals; accounting for materials; finances; 12 appendices.*

Report of the Committee on the Measurement of Geologic Time, 1947–1948. JOHN PUTNAM MARBLE, Chairman. Pp. 77. Division of Geology and Geography, National Research Council, Washington, D. C., June 1949. Price, $1.00. *Summary report; 5 supplementary reports presented as exhibits and annotated bibliography.*

Hydrology. Edited by OSCAR E. MEINZER under the auspices of the NATIONAL RESEARCH COUNCIL. Pp. 714; figs. 165; tbls. 23. Dover Publications, Inc., New York, 3rd Impression, 1949. Price, $4.95. *A reprinting of a book that made a name for itself; published in 1942 and reviewed then.*

Minerals in World Affairs. T. S. LOVERING. Pp. 394; figs. 40; tbls. 51. Prentice-Hall, Inc., New York. Price, $4.00. *New printing of an excellent book.*

Structural Geology. MARLAND P. BILLINGS. Pp. 473; figs. 336; pls. 19. Prentice-Hall, Inc., New York. Price, $4.75. *Fifth printing of the well-known book.*

Batholith and Associated Rocks of Corona, Elsinore, and San Luis Rey Quadrangles, Southern California. ESPER S. LARSEN, JR. Pp. 182; figs. 16; pls. 8. Geol. Soc. America Mem. 29, New York, 1948. *Batholith intrudes Triassic sediments and Jurassic (?) volcanic rocks along western border and Paleozoic sediments along eastern border. Batholith must have been emplaced by stoping, not by forceful injection; its different rocks were formed from the intermediate gabbro by crystal differentiation and assimilation in depth.*

Geology of the Lake Titicaca Region, Peru and Bolivia. NORMAN D. NEWELL. Pp. 111; figs. 14; pls. 21. Geol. Soc. America Mem. 36, New York, March 1949. *Present topographic basin appears to result from block faulting and stream erosion; indications that recently the water level fell more than 100 meters. Most intrusives are hypabyssal, dating probably from older stages of vulcanism. One chapter devoted to Pirín, the highest petroleum field in the world.*

Laboratory Manual for Elementary Physical Geology. ROBERT O. BLOOMER. Pp. 77 (lithographed); tbls. 12; pls. 12. L. C. Grandy, Syracuse, N. Y., 1949. Price, $1.70.

Differential Thermal Analysis of Reference Clay Mineral Specimens. PAUL F. KERR, J. LAURENCE KULP, AND P. K. HAMILTON. Pp. 48; figs. 27; pl. 1; tbls. 3. Am. Petroleum Inst. Project 49, Clay Mineral Standards, Prel. Rept. 3, Columbia University, New York, May 1949. *Method, theory, apparatus, procedure, and sample preparation; experimental results for various groups in different localities; bibliography.*

Endellite Deposits in Gardner Mine Ridge, Lawrence County, Indiana. EUGENE CALLAGHAN. Pp. 47; figs. 4; pls. 7. Indiana Dept. Conservation, Div. of Geology, Bull. 1, Bloomington, June 1948. Price, $1.25. *Endellite with minor halloysite and allophane or allophane-evansite; bodies of clay occur at erosional contact of Pennsylvanian Mansfield sandstone with underlying Mississippian formations of Chester group or as cavity fillings within sandstone, subsequently changed to endellite; non-ferruginous endellite bodies estimated at about 20,000 tons.*

Kansas Geological Survey—Lawrence, 1949.

Scenic Kansas. KENNETH K. LANDES. Pp. 15; photos 19. *For the layman.*

Oil and Gas in Eastern Kansas, with Special Reference to Developments from 1944 to 1948. JOHN MARK JEWETT. Pp. 308; figs. 53; pls. 4; tbls. 81. Univ. of Kansas Publications Bull. 77. *Stratigraphy and major structural features in eastern Kansas; study by county.*

Conference on Radioactive Ores. A. K. SNELGROVE, Editor. Pp. 31. Michigan College of Mining and Technology, Houghton, May 6, 1949. *Contains articles on domestic uranium program of the U. S. Atomic Energy Commission; pitchblende—the primary source of uranium; the geologic environment of primary vein deposits of uranium; inspection of radiations laboratory; uranium deposits of the Canadian Shield, with emphasis on the Theano Point, Ontario; Geiger counter reconnaissance in Upper Michigan; prospecting for uranium with portable Geiger-Muller equipment; prospecting on state land in Michigan; symposium on field plans.*

Stratigraphy of North Dakota with Reference to Oil Possibilities. WILSON M. LAIRD. 2 sheets 34″ x 22″, with 2 tables, 13 figs. North Dakota Geological Survey Rept. Inves. 2, Grand Forks, 1949. *Short text on general structure and stratigraphy.*

Brick and Tile Industry in Oregon. JOHN ELIOT ALLEN AND RALPH S. MASON. Pp. 28; figs. 3; tbls. 3. Oregon Dept. Geology and Mineral Industries Short Paper 19, Portland, 1949. Price, 20 cents. *Description of clay plants and results of tests.*

Bureau of Economic Geology, University of Texas—Austin, 1949.

Rept. Inves. 4. Correlation of Gravity Observations with the Geology of the Coal Creek Serpentine Mass, Blanco and Gillespie Counties, Texas. FREDERICK ROMBERG AND VIRGIL E. BARNES. Pp. 11; figs. 4.

Publ. 4915. Clay Deposits of the Cisco Group of North-Central Texas. F. P. PLUMMER, H. B. BRADLEY AND F. K. PENCE. Pp. 44; figs. 34; pls. 8. Price, $1.00. *Geology of the various clay deposits; ceramic technology of the clays.*

Geology of Kootenay Coal Measures in Southwestern Alberta. M. B. B. CROCKFORD. Pp. 7; figs. 4; tbls. 2. Research Council of Alberta Contr. 15, March 1949.

Ontario Department of Mines—Toronto, 1949.

General Index to the Reports, Vols. 36 to 49, 1927–1940. Compiled by E. A. TREVOR. Pp. 505. *Usual alphabetical index.*

57th Annual Report, Vol. 57, Pt. II, 1948. Mines of Ontario in 1947. STAFF OF MINES INSPECTION BRANCH. Pp. 123; numerous tables. *Alphabetical list of minerals and mine by mine description.*

57th Annual Report, Vol. 57, Pt. III, 1948. Natural Gas in 1947. Petroleum in 1947. R. B. HARKNESS. Pp. 96; tbls. 18; figs. 4.

Canadian Mines Handbook 1949. Pp. 360. Northern Miner Press Limited, Toronto, July 1949. *Part I, principal companies; Part II, supplementary list, including inactive and extinct companies. This year 760 active companies against 842 last year; 7,705 inactive against 7,477 a year ago. Most important new feature is inclusion of about a dozen asbestos mining companies, including some of the whole mining industry's largest tonnage operations. Another highlight is new developments in uranium.*

Report on the British Guiana Geological Survey Department for 1947. Pp. 39; pls. 3. Georgetown, 1948. Price, 48 cents. *Usual report on field and laboratory work, publications, proposals for expansion; 8 short papers as appendices.*

Petrology of the Northampton Sand Ironstone Formation. J. H. TAYLOR. Pp. 111; figs. 10; pls. 7; tbls. 9. Great Britain Dept. of Scientific and Industrial Research, London, 1949. *Yields more than half of British iron ore; stratigraphy, chemistry, petrology, origin; 4 plates of colored photomicrographs.*

A Prospector's Handbook to Radioactive Mineral Deposits. C. F. DAVIDSON. Pp. 28. Atomic Energy Division, Geol. Survey and Museum, London, 1949. Price, 6d (20 cents). *Description of common radioactive minerals; radioactive mineral deposits; how to test for radioactivity; the market for radioactive minerals.*

Fourth Empire Mining and Metallurgical Congress—Great Britain, July 1949.

Pap. AB–1. Mineral Industry of Australia with Particular Reference to the Past Twenty Years. P. B. NYE, I. C. H. CROLL, AND D. R. DICKINSON. Pp. 18; tbls. 2; map 1. *Short text on each metal or mineral, alphabetically; table showing mineral production from 1939 to 1948 by product.*

Pap. AB–2. Some Notes on the Mineral Resources (Excluding Coal) of Union of South Africa. A. R. MITCHELL. Pp. 12; appendices 2.

Pap. AB–3. Changes in Canada's Mineral Resources During the Past Ten Years. G. C. MONTURE. Pp. 18; figs. 2; tbls. 5. *Most important development is titanium deposit at Allard Lake; estimates 150 million tons or more of ilmenite; mercury also improved much.*

Pap. AB–4. The Mineral Resources of Malaya and Other Far Eastern Countries. LEWIS LEIGH FERMOR. Pp. 31; tbls. 8. *Malaya's production interrupted by the depression, then by the Japanese occupation, is now progressing, except for iron and manganese. Borneo, with its Seria oilfield, has an amazing post-war development. Immense possibilities of mineral development.*

Pap. AB–5. The Mineral Resources of the British West African Colonies. N. R. JUNNER. Pp. 16; pls. 3; tbls. 2. *Description of principal mineral deposits of Nigeria, Gold Coast and Sierra Leone, with emphasis on mineral discoveries and progress in the past 20 years.*

Pap. AB–6. The Mineral Resources of the East African Colonies. EDMUND O. TEALE. Pp. 20; pl. 1; tbls. 5; figs. 4. *Promising prospects; most important was discovery of rich occurrence of diamonds at Mwadui, Tanganyika, in 1943.*

Pap. AB–7. Mineral Resources of India. D. N. WADIA. Pp. 20; tbls. 2; 1 map 18″ × 17″. *Mineral by mineral.*

Pap. AB–8. Significant Changes in the Known Position of the Mineral Resources of Southern Rhodesia During the Past 20 Years. J. C. FERGUSON. Pp. 9; tbls. 2. *Most important still gold.*

Pap. AB–9. The Mineral Resources of Other Empire Territories. E. H. BEARD. Pp. 30; tbls. 4. *Significant changes in the last 20 years; important development of copper industry in Northern Rhodesia; petroleum and asphalt in Trinidad; bauxite in British Guiana; copper bearing minerals in Cyprus; minor mineral developments in Jamaica, Swaziland, Nyasaland, Bechuanaland.*

Pap. C–1. Aerial Photography in Petroleum and Mineral Prospecting. A. A. FITCH, D. F. CHRISTIE, W. E. JOHNSTONE, AND G. WHITTLE. Pp. 31; figs. 4; 5 photogeological maps in color.

Pap. C–2. Modern Methods of Mineral Exploration in South Africa. LOÛIS T. NEL, D. J. SIMPSON, AND JOHN DE VILLIERS. Pp. 23. *Description of methods of geophysical prospecting, aerial photography and core drilling, necessary to discover new deposits.*

Pap. C–3. Mineral Exploration in Australia. C. J. SULLIVAN. Pp. 25. *Geochemical studies and venture diamond drilling started recently.*

Pap. C–4. Modern Methods of Mineral Exploration in Canada. FRANC R. JOUBIN. Pp. 20.

The Study of the Soils of Guntur District in Relation to Geology. NARASINGO SATHAPATHI. **Mechanical Analysis of Some Gondwana Sandstones from Southwest Corner of Raniganj Field.** SAURINDRANATH SEN AND SUNILKUMAR RAYCHAUDHURI. Pp. 25; figs. 9; tbls. 20. Geol. Min. Met. Soc. India Quart. Jour., Vol. 20, No. 3, Sept. 1948.

Geología de los Yacimientos de Fierro de Chile. HÉCTOR FLORES. Pp. 15; tbls. 4. Minerales, No. 28, March 1949, Santiago de Chile. *Geology, production, and reserves of the iron deposits of Chile.*

Notas sobre Fertilizantes Fosfatados. JAYME BENEDICTO DE ARAUJO AND CASSIO MENDONÇA PINTO. Pp. 5; tbls. 3; figs. 3 (in Portuguese). Departamento Nacional da Produção Mineral, Avulso 8, Rio de Janeiro, 1948. *Apatite from Araxá and the industry of fertilizers; solubility of mineral phosphates by desfluorization; solubility of some mineral phosphates.*

Geofisica Pura e Applicata. Pp. 144; figures and tables. Vol. 14, Fasc. 1–2, Milan 1949. *In Italian, German, Spanish, and French with English summaries. Several papers on geophysical subjects.*

Das Leitmotiv der Geotektonischen Erdentwicklung. HANS STILLE. Pp. 27; figs. 10. German Acad. Sci. Rept. 32, Berlin 1949. *Development of major structural features.*

Annales de la Société Géologique de Pologne—Krakow, 1946 and 1948.

Tome 16. Pp. 252; numerous tables and illustrations (in Polish). *Several papers; geological structure of Wilno and surroundings; stratigraphy of the Quarternary deposits in the Bug-river basin; the Silurian rugose corals from Podolia; the dolomite of Imielin; on the Tertiary and Quarternary of the Baltic shore between Wielka Wies and Jastrzebia.*

Tome 17. Pp. 340; numerous tables and illustrations (in Polish). *Miocene of the northern border of the Carpathians; geological conditions of the origin of blue salt, amethyst and violet fluorite; the Carpathes gravels of "antropogenetic" origin; role of quartzites in the Tatra gravels; a porphyry in the Czernka valley; current bedding in Carpathian Flysch; the Skole nappe in the region of the Czeremosz; contribution to the knowledge of the Miocene of Poland.*

SOCIETY OF ECONOMIC GEOLOGISTS

THIRTIETH ANNUAL MEETING JOINTLY WITH GEOLOGICAL SOCIETY OF AMERICA AND ASSOCIATED SOCIETIES.

HOTEL HILTON

EL PASO, TEXAS

November 10, 11, 12, 1949.

Hotel Hilton Ball Room, 9:00 A.M. Thursday, November 10.

Mineral Resources: William B. Heroy and T. M. Broderick, Co-Chairmen.

9:00 John M. Hills and E. Russell Lloyd
Oil Resources of area tributary to El Paso

9:25 Nelson Sayre
Ground-water resources of area tributary to El Paso

9:50 Harrison Schmitt
Mineral resources of area tributary to El Paso

10:15 H. B. Stenzel
Coals of Texas

10:40 Chas. H. Behre, Jr., George L. De Coster, Peggy-Kay Hamilton, and Charles Seel
Patterns of ore deposition in Mexico

11:00 Meeting to break up at 11:00 to permit setting up SEG luncheon in same room.

Hotel Hilton Ball Room, 2:30 P.M. Thursday, November 10.

Mineral Deposits: Philip Shenon and Charles Park, Co-Chairmen.

2:30 C. D. Campbell
Favorable ore zones of the Northport District, Washington

2:50 Vard H. Johnson
Geology of the Helvetia Mining District, Pima County, Arizona

3:10 Robert G. Yates and George A. Thompson
Origin of the Mercury minerals of the Terlingua District, Brewster and Presidio Counties, Texas

3:30 M. Gordon, Jr., J. I. Tracey, and M. W. Ellis
Field relations of Arkansas bauxite deposits

3:50 Harrison Schmitt
Origin of the epithermal mineral deposits

4:10 Kenneth K. Landes
Metallurgical limestone reserves

Hotel Cortez Ballroom, 9:00 A.M., Saturday, November 12.

Economic Geology: A. E. J. Engel and D. M. Davidson, Co-Chairmen.

9:00 R. M. Garrels, A. L. Howland, R. M. Dreyer
Precipitation of basic copper

9:20 R. M. Dreyer, A. L. Howland, R. M. Garrels
Wallrock replacement by oxidized copper minerals

9:40 J. V. N. Dorr II and Philip W. Guild
Notes on the iron ores of central Minas Gerais, Brazil

10:00 Jan Kutina
Scheme of the chemistry of the ore veins based on qualitative spectrographic analysis

Hotel Hilton Green Room, 2:30 P.M., Thursday, November 10.

Coal Research Symposium: George H. Ashley and G. H. Cady, Co-Chairmen.

2:30 R. P. Bryson
Distribution, occurrence, and resources of sub-bituminous coal and lignite in the western United States

3:00 V. P. Parry
Production, classification and utilization of western U. S. coals

3:30 B. R. MacKay
Canada's resources of low-rank coals

4:00 H. B. Stenzel
Texas low rank coals

4:30 W. B. Roe
Geological features of North Dakota lignites

Hotel Hilton Ball Room, 2:00 P.M., Friday, November 11.

Coal Research Symposium, continued: Charles H. Behre and J. M. Schopf, Co-Chairmen.

2:00 Elso S. Barghoorn
Geological and botanical study of the Brandon lignite and its significance in coal petrology

2:30 B. C. Parks
Petrography of American lignites

3:00 Paul Averitt
Status of work on coal resources in the United States

3:30 R. M. Kosanke
Review of coal research 1948–1949

The Annual Luncheon of the Society will be held in the Hotel Hilton Ball Room at noon, Thursday, November 10. T. B. Nolan, President of the Society, will deliver his Presidential Address at that time.

Abstracts of papers to be presented at the Thirtieth Annual Meeting in conjunction with the Geological Society of America and Associated Societies, El Paso, November 10–12, 1949.

GROUND-WATER RESOURCES OF THE EL PASO REGION.[1]

ALBERT NELSON SAYRE.

The El Paso region is arid to semiarid. The precipitation ranges from about 20 inches on the High Plains to 8 inches, or less, near Deming, New Mexico. The only perennial streams are the Rio Grande, the Pecos, and the Gila, and these have few perennial tributaries; thus, water supply assumes major importance in the life and economy of this region. Surface-water resources have been essentially fully developed and appropriated, mostly for irrigation. Ground-water resources appear to have been developed nearly to their maximum for irrigation, municipal, and domestic use at most places on the American side, but substantial supplies are probably available at several places on the Mexican side. Ground water provides all or most of the supply for each municipality in the area, including El Paso and Ciudad Juarez, and is used to irrigate large acreages in the Roswell Basin, the High Plains of New Mexico and Texas, near Pecos and Fort Stockton in Texas, and near Deming in New Mexico. Some of the ground-water reservoirs are enormous and contain huge quantities of water in storage. However, the replenishment is generally small in comparison with the annual pumpage. Thus, the supplies are being depleted in several areas. Exhaustive investigations have been made to determine the amount of ground water in storage and the average rate of replenishment in the area surrounding El Paso, the Roswell Basin, the Deming area, the High Plains, and the Pecos and Fort Stockton areas.

COALS OF TEXAS.

H. B. STENZEL.

The first record of a coal mine in Texas dates from 1819 and refers to a "mine de charbon de terre" in the brown coal region of east Texas. The peak of production was attained in 1914 to 1918 for the brown coals and 1912 to 1913 for the bituminous coals. Mining of bituminous coals has practically ceased and that of brown coal is greatly reduced.

Usable coals occur in the Pennsylvanian formations of north central Texas, the Eocene formation (Wilcox group chiefly) of the Gulf Coastal Plain, and the upper Cretaceous formations of the Rio Grande region.

PATTERNS OF ORE DEPOSITION IN MEXICO.

CHAS. H. BEHRE, JR., GEORGE L. DE COSTER, PEGGY-KAY HAMILTON, CHARLES SEEL.

Mexican mineral deposits are intimately related to the regional history of the four metallogenic provinces. This tentative summary is based on approximately 18 months of field work and data furnished by cooperative mining companies, individual geologists and engineers, and Mexican and U. S. A. federal geological agencies.

Broadly, the four metallogenic provinces recognizable, with overlaps and exceptions, differ stratigraphically and structurally. The Sonoran Province, char-

[1] Footnote 1 indicates published by permission of the Director, U. S. Geological Survey.

acterized by copper and non-ferrous metals and some precious metal values, is one of Paleozoic and Precambrian rocks and cross-cutting intrusions; mineralization is closely linked to intrusive processes. The Plateau Province is typified by lead-zinc ores with or without silver values; here intrusives localized some deposits, but distribution seems mainly controlled by arching and related faulting. The Southern Province is chiefly one of mineralization in schists; cupriferous pyrite is here a prominent ore with local precious metal values. The Cordilleran Province, lying athwart a connection between the Sonoran and Southern Provinces, is in faulted lavas and pyroclastics; mineralization is chiefly in its stratigraphically lower (andesitic) reaches and still deeper rocks; here high precious metal values preponderate.

The major base and precious metals are widely distributed in Mexico. Iron ores are chiefly confined to contact replacements. Mexico may be described as characterized by lead-zinc-silver mineralization (linked to the large Cretaceous limestone areas of its Plateau Province) and by bonanza precious metal ores. Widespread are also important mercury and antimony deposits and economically insignificant tin ores.

FAVORABLE ORE ZONES OF THE NORTHPORT DISTRICT, NORTHEASTERN WASHINGTON.[1]

CHARLES D. CAMPBELL.

The relative abundance of lead, zinc, and silver in dolomites of the Northport district appears to depend on the stratigraphic position of the deposits within the Metaline limestone and the upper 900 feet of the underlying Maitlen phyllite both of Cambrian age. The most favorable zone extends from 3,400 to 4,500 feet below the top of the 6,000-foot thick Metaline limestone. Twenty-nine percent of the estimated lead production in the district, 89 percent of the zinc, and 20 percent of the silver came from this zone. Most of the deposits in this part of the section are sulfide replacements in fractures. In stratigraphic units outside the favorable zone the metals are less abundant, and the proportion of the three metals differs.

Correlation of ore type with stratigraphic position may be due to:

(1) development of more favorable structures for ore deposition in some zones than in others, dependent on the manner in which the rocks respond to stress;

(2) the varying proportions of the metals in different beds which may reflect original differences in chemical composition of the beds. There is no evidence of regular concentric zoning.

A series of maps, each showing the outcrop of one ore horizon and the position of faults, shear zones, or other structural features that might localize ore in that horizon, would be a valuable guide to exploration and prospecting, but detailed mapping of the structure and stratigraphy of the entire potentially mineralized area is required before these maps can be drawn.

GEOLOGY OF THE HELVETIA MINING DISTRICT, PIMA COUNTY, ARIZONA.

VARD H. JOHNSON.

Helvetia, one of the minor copper mining districts of Arizona, shows the complex structural relations which are typical of the mining areas of Southern Arizona.

Paleozoic sediments, mostly calcareous, were intruded by a post-Permian granite which was, in turn, intruded by an alaskite granite of Tertiary age. Cretaceous sediments, formed largely of the older igneous material, were faulted and intruded by the alaskite granite and by diorite dikes. Dikes of diabase and basalt are present also. Normal and reverse faulting accompanied both major intrusions. Copper, silver, lead, zinc, tungsten and molybdenum have been mined at Helvetia. All of the ore bodies are in the contact metamorphic zone or in replacement bodies and fissure veins near the contact. Local evidence is insufficient to show whether the ore deposits are genetically related to the emplacement of the post-Permian granite or the alaskite granite, as the ore bodies occur at the contacts of both intrusives with calcareous sediments.

ORIGIN OF THE MERCURY MINERALS OF THE TERLINGUA DISTRICT, BREWSTER AND PRESIDIO COUNTIES, TEXAS.[1]

ROBERT G. YATES AND GEO. A. THOMPSON.

The Terlingua district, in the southern part of the Big Bend section of Trans Pecos, Texas, has produced more than 150,000 flasks of quicksilver. Quicksilver minerals are in veins and tabular pipelike bodies in limestone, clay, and intrusive igneous rock. The common associated minerals are calcite, clay, pyrite, and hydrocarbon compounds. Cinnabar is the principal ore mineral, but mercury also is found as the native element, and as montroydite, calomel, and mercury ammonium chlorides. The chloride minerals, long considered supergene, are believed by the authors to be hypogene, and the evidence for their hydrothermal origin from magmatic waters is presented. The cinnabar is believed to have been deposited from the same waters at a lower temperature through the precipitating action of hydrogen sulfide upon mercury in solution.

FIELD RELATIONS OF ARKANSAS BAUXITE DEPOSITS.[1]

MACKENZIE GORDON, JR., JOSHUA I. TRACEY, JR., AND MILLER W. ELLIS.

Studies by the U. S. Geological Survey during the war show that four principal types of bauxite deposits can be recognized in the Arkansas bauxite region. Their occurrence is controlled by the nature of the source rocks, by the physiography of the ancient land surface on which they formed, and by the stratigraphic history of the region.

(1) Residual deposits on higher slopes of buried nepheline syenite hills have a lower zone, preserving the granitic texture of the original rock from which they weathered, and an upper concretionary zone. They are separated from fresh nepheline syenite by kaolinitic clay that, adjacent to the bauxite, appears massive or fragmental.

(2) Colluvial deposits on lower slopes along the buried edge of sediments of the Midway group have a lower zone locally preserving clay textures, a thicker concretionary zone above, and commonly up slope a siliceous hardcap. They grade into a surrounding kaolinitic envelope. Their deposition was contemporaneous with that of early Wilcox lignite, gray clay, and sand further down slope.

(3) Alluvial deposits, composed of stratified, sorted, and cross-bedded pebbles, pisolites, and grains of bauxite, overlie and fill channels in colluvial bodies and tongue into the early Wilcox sediments.

(4) Alluvial deposits, mostly bauxite boulder beds, overlie residual deposits or early Wilcox sediments and tongue into later Wilcox sediments, particularly as

the basal conglomerate of a dark chocolate-brown clay and sand unit that unconformably overlies the lignite, gray clay, and sand unit.

The first two types are the source of most of the ore in the region, but all four have been mined.

ORIGIN OF THE EPITHERMAL MINERAL DEPOSIT.

HARRISON SCHMITT.

The environment during the formation of epithermal mineral deposits is likely to be duplicated in modern areas of fumaroles and hot springs. If this is assumed various implications follow: the exotic elements including the ore metals are brought in by the volcanic emanations, meteoric water plays a dominant role, the chemistry of the mineral bearing liquids is primarily one conditioned by carbon dioxide, hydrogen sulfide and atmospheric oxygen, the silica is mainly derived from wall rock alterations and the vadose circulation may be from the walls to the vein, or down and up in the vein itself as well as from the main fissures to the walls.

More general implications include: an obvious explanation for the shallow bottomings of epithermal ore shoots, the fine banding in epithermal ores, and the intricate intermingling of hypogene and supergene phenomena. Further, since the origin of the silica does not depend on a magma the postulation of the magma as the ultimate source is weakened.

METALLURGICAL LIMESTONE RESERVES.

KENNETH K. LANDES.

"Metallurgical limestone" as here used includes both limestone and dolomite which are of such quality as to be suitable for blast furnace flux, open hearth flux, furnace linings, lime burning and chemical manufacture. The specifications vary with the use, but within any one use classification there is very little latitude possible in regard to either chemical composition or physical character. Contrary to usual opinion the reserves of limestone suitable for metallurgical operations are by no means unlimited. With very few exceptions the high grade limestone deposits being exploited today will be exhausted during the next 50 years.

PRECIPITATION OF BASIC COPPER.

R. M. GARRELS, A. L. HOWLAND, AND R. M. DREYER.

The precipitation of pH of basic copper chloride (atacamite) and basic copper sulfate (brochantite) was determined at 25° C and 45° C over a wide range of concentration of the original copper chloride and copper sulfate solutions. Precipitation was induced by addition of sodium hydroxide. The same compounds precipitated at the surface of calcite or dolomite rhombs immersed in copper chloride or copper sulfate solutions. The mechanism indicated is a local neutralization of acidity at the mineral surface as hydrogen ions from solution react with carbonate ions of the dolid, permitting the formation of the basic copper mineral in this neutralized zone. All experimental work indicates that basic copper carbonate such as malachite or azurite does not form by direct reaction of copper bearing solutions with carbonate rocks. The precipitated atacamite and brochantite are very fine-grained, with a tendency to "weld" and form an impervious coating

on the calcite or dolomite. However, aging of the original precipitate seems to occur eventually causing increase in grain size and in porosity of the precipitated layer.

WALL ROCK REPLACEMENT BY OXIDIZED COPPER MINERALS.

R. M. DREYER, A. L. HOWLAND, AND R. M. GARRELS.

Initial deposition of copper carbonates and copper silicates as crustifications or replacements in carbonate wall rocks occurs, in many places, as clusters of radiating needles. Complete replacement may be effected by the coalescence of such clusters. Crustification over spherical clusters may produce a botryoidal surface. A replacement layer may contain several alternating colloform bands of copper carbonates and copper silicates. A variation has been noted in the composition of chrysocolla.

THE PARAGENESIS OF ACCESSORY MINERALS IN IGNEOUS ROCKS.

W. W. MOORHOUSE, P. A. PEACH, AND R. M. BUCHANAN.

Textural and statistical evidence is presented to show that non-opaque accessories of igneous rocks (such as apatite, sphene, zircon) crystallized late in the crystallization history of the rock.

SCHEME OF THE CHEMISTRY OF THE ORE VEINS BASED ON QUALITATIVE SPECTROGRAPHIC ANALYSIS.

JAN KUTINA.

The chemistry of the ore veins is represented by a diagram showing all stated elements including the trace quantities, with reference to the ore veins from St. Anthony de Padua mine near Poličany, SW. of Kutná Hora (Bohemia).

1. The paragenetic sequence of all discussed minerals as determined on polished sections is shown diagrammatically. 2. From spectrographic analyses of the minerals the elements present have been assigned by visual estimation to three categories: large, small, and trace. 3. In the diagram showing the chemistry of the ore veins the elements are on the ordinate and on the abscissa the variation in amounts of the elements during various periods of crystallization. Also noted is the abundance of the various minerals in different generations.

From the diagram one can observe the quantitative relationship of elements at different temperatures during the genesis of the ore veins. For example, the arsenic is concentrated at the highest temperatures and at the lower temperatures it occurs in traces only; in general the reverse is true with antimony. The chief concentration of many elements is preceded in the succession by trace amounts in the older minerals and by traces in the younger ones. Some of the elements appear to be unaffected by temperature, *e.g.* iron.

The dependence upon temperature, however, must be considered with possibilities of isomorphous substitution (Cd, Ga, In, etc.) and the problems of exsolution.

DISTRIBUTION, OCCURRENCE, AND RESOURCES OF SUB-BITUMINOUS COAL AND LIGNITE IN THE WESTERN UNITED STATES.[1]

ROBERT P. BRYSON.

In the western United States vast reserves of sub-bituminous coal and lignite, which have not been extensively developed to date because of their limited competitive position, are known to exist in several regions in beds, some thick and extensive and others thin and lenticular, that are associated with nonmarine sedimentary strata of Upper Cretaceous, and lower Tertiary age. These reserves are located in California, Oregon, Washington, Idaho, Montana, North Dakota, South Dakota, Wyoming, Colorado, Utah, Arizona, New Mexico, and Texas.

West of the Rocky Mountain front the coal-bearing rocks dominantly are Upper Cretaceous in age. Where they are exposed, commonly they dip inward at the margins of structural basins, some of which may also have been separate basins of deposition at the time the coal was deposited. Individual coal beds commonly are lenticular in cross section and can be traced at most only a few miles along the outcrop. East of the Rocky Mountain front the coal-bearing rocks dominantly are lower Tertiary in age and are nearly flat or dip gently eastward away from the mountains. Especially in the Fort Union and Powder River Regions some individual coal beds can be traced across hundreds of square miles.

Recent reserves estimates for some states, based on data obtained by systematic examination and mapping of western coal lands by the U. S. Geological Survey and by work of other organizations and individuals, are found to agree in general though not in detail with earlier published estimates. More than nine-tenths of the sub-bituminous coal reserves of the United States are in Wyoming, Montana, and Colorado; and more than nine-tenths of the lignite reserves are in North Dakota and Montana.

PRODUCTION, CLASSIFICATION, AND UTILIZATION OF WESTERN U. S. COALS.

V. F. PARRY.

Western coals comprising the Rocky Mountain and Northern Great Plains Provinces represent approximately 60 percent of the estimated U. S. solid fuel reserve but production from these fields since 1920 decreased from 7 to about 5 percent of the national bituminous production. The reason for decline is clear because oil and gas produced in the West has increased from the equivalent of 133 to 526 million barrels of oil in the same period. The total production of mineral fuels in the western states is now equivalent to 650 million barrels of oil but coal supplies less than 18 percent of this energy. The energy demand from mineral fuels will expand but the forms of energy produced will shift as the costs vary. Without oil or natural gas, about 170 million tons of coal would be required but coal supplied only 31 million tons in 1945. The long-range picture for coal looks bright but the immediate demand for western coal is relatively low.

Coal is produced in 47 western mining areas, distinguished by locality and difference in quality. (Three charts of the fields are shown.) Although the average heating value of western coal is 11,400 B.t.u. per lb. (U. S. avg. = 13,500), the individual mining areas produce 6,700 to 13,700 B.t.u. coals which are predominantly non-coking with natural moisture varying up to 40 percent. Western

coals are characterized by high volatile content and they are relatively highly reactive chemically which is favorable for manufacture of synthetic liquid fuels.

The paper includes charts showing improved methods for classifying western coals for the chemical engineer and illustrating their properties, utilization, and occurrence.

CANADA'S RESOURCES OF LOW-RANK COALS.[2]

B. R. MACKAY.

Canada's low rank coals are largely concentrated in the plains region of Alberta and Saskatchewan. Those of Alberta are mostly sub-bituminous, and occur in the Foremost, Oldman, and Edmonton formations of the Upper Cretaceous. The deposits of Saskatchewan are entirely lignite and occur in the Upper Cretaceous in the eastern extensions of the Foremost and Oldman formations of Alberta. The main deposits occur in the Ravenscrag formation of the Tertiary Paleocene age which correlates with the Fort Union formation, Fort Union region of Montana and North Dakota. Numerous scattered deposits of low rank coal, mainly lignite, and mainly of Tertiary age, are found in British Columbia, Yukon, Northwest Territories, and James Bay region.

The reserves of low rank coals of Alberta are approximately 874 billion metric tons; those of Saskatchewan approximately 60 billion metric tons; the remaining low rank coals are estimated as approximately 15 billion metric tons. Previous estimates by Dowling (1913) were based upon erroneous assumptions in regard to the continuity of the coal beds. The change from fresh water sedimentation in western Alberta to marine deposition in the east is now known to parallel progressive thinning of the coal beds.

Present estimates are based upon computations for the Royal Commission on Coal, 1946, and are confined to coal seams more than 3 feet thick lying at recoverable depths.

Extensive areas in Alberta and elsewhere in western Canada are probably underlain by workable coal beds but data available do not warrant a reliable estimate.

GEOLOGICAL FEATURES OF NORTH DAKOTA LIGNITES.

WALTER B. ROE.

North Dakota lignites occur in the Fort Union and upper part of the Lance Formations. Individual seams vary from a few inches to over forty feet in thickness. The lignite horizons are quite continuous over large areas, but the individual seam representing a particular horizon is often lenticular and of limited extent horizontally.

Underclays are conspicuously absent. The lignite is woody in character and brown in color. Ash is low and sulfur conspicuously so and moisture is high. There is indication of cyclical sedimentation.

GEOLOGICAL AND BOTANICAL STUDY OF THE BRANDON LIGNITE AND ITS SIGNIFICANCE IN COAL PETROLOGY.

ELSO S. BARGHOORN.

Although virtually unknown in the northeastern United States, Tertiary strata occur in limited areas in western New England. By far the most significant of these Tertiary horizons is a small area at Brandon, Vermont.

[2] Published by permission of the Director of Mines, Forests and Scientific Services.

Lignite, of Mid- or early Tertiary age, associated with kaolin, ocher and oxide ores of iron and manganese occurs here in close proximity in a very restricted area. The recognizable plant tissues in the lignite consist entirely of the remains (fruits, seeds, pollen and wood) of hardwood trees and shrubs. No coniferous woods have been found. The deposit is devoid of bedding planes, yet is composed primarily of water-transported plant fragments, admixed with quartz pebbles and sand. Structural preservation of the constituent plant tissues is exceptionally good, permitting detailed anatomical study and accurate identification of the plant components of the lignite. In addition to wood fragments and attritus the Brandon deposit is featured by the abundance of well preserved fruits and seeds. The total flora of the lignite comprises over 100 species, or which approximately one-fourth have been botanically determined. Analyses of discrete plant fragments have been made with reference to the anatomical, physical and chemical changes which occur during lignitization. These studies have provided new analytical data and further understanding of the complex processes which feature the transformation of plant tissues into coal.

PETROGRAPHY OF AMERICAN LIGNITES.

B. C. PARKS.

The extensive deposits of low-rank coal in the United States are receiving more than usual attention as a result of declining reserves of competitively more favorable coals and development of important non-fuel uses of coal. Use of domestic lignite for solvent extraction of montan wax to replace foreign supply cut off from American industry is an example.

This paper describes briefly occurrences of lignitic coals in the United States, and includes discussion of terminology, petrographic composition, coalification, and rank classification of these coals.

Certain tests are described and data presented showing results of petrographic investigation of the source of wax and resin in lignite. Purpose of the investigation was to determine the components in lignite contributing to the solvent extraction products, and the phyteral source of "waxy," "resinous," and asphaltic elements in the extracts.

Certain varieties of attrital lignite proved to be the most important source material of waxy solvent extracts. "Pure" attrital lignite of known high solvent yield was broken down by a method of chemical maceration which removed humic matter and freed various ingredients of the attritus, mostly yellow translucent matter. Phyteral components in the residue were spores, pollen, particles of lump-type resin, round, light and dark resinous bodies, dark "resinous" rodlets, remains of petioles, and cuticular matter.

A microscope hot stage was used to observe the effect of heat on these various ingredients and their solvent products. Information resulted which indicated that for attrital lignites tested the wax in solvent extracts is derived mainly from cuticular remains, resin from lump-type resin and round resinous bodies, and asphaltic material probably from dark "resinous" bodies. The discovery of wax associated with cuticular remains is in keeping with the known fact that in living plants wax is found exclusively in cuticular coverings of leaves, petioles, and reproductive organs, and in suberin. Origin of attrital and xyloid lignites is discussed.

STATUS OF WORK ON COAL RESOURCES IN THE UNITED STATES.[1]

PAUL AVERITT.

An appraisal of both detailed mapping in coal field areas and summary studies of coal reserves in the United States, carried on by State and Federal Agencies during 1949 with a listing of projects completed or known to be in progress.

REVIEW OF COAL RESEARCH, 1948–1949.

R. M. KOSANKE.

The literature for 1948–1949, exclusive of resource studies, is reviewed in this paper. In some cases, foreign publications prior to 1948 are included because they have been made available to us during the past year. For convenience, the publications have been classified under the following topics: origin and metamorphism of coal, coal petrography, paleobotany, geochemistry, and coal mining. This is in line with suggestions made at the March 1949 meeting of the Coal Research Committee of the Society of Economic Geologists held at the Bureau of Mines, Pittsburgh, Pennsylvania.

NOTES ON IRON ORES OF CENTRAL MINAS GERAIS, BRAZIL.[1]

JOHN VAN N. DORR, II, AND PHILIP W. GUILD.

Preliminary results of a continuing cooperative research project of the United States Geological Survey and the Brazilian Departamento Nacional da Produção Mineral on the geology and hematite ores of Central Minas Gerais are summarized.

For economic purposes the ores can be divided into three types:

a) hard lump ore averaging about 68% Fe.
b) fine to powdery ore averaging approximately 68% Fe.
c) soft, easily concentrated quartzose protore averaging perhaps 50% Fe.

Although type a is the only one now being exported, the other types will have to be mined to produce lump ore on a large scale. Therefore either exportation of run-of-mine ore or concentration or reduction in Brazil of the finer ores seems logical. The sale abroad of concentrates or pig iron would pay for the importation of needed fuel.

Field work suggests that the Brazilian iron formation, itabirite, is a metasediment derived from banded iron oxide—jasper rock similar to much of the iron formation of the Lake Superior region. Many bodies of pure hematite are demonstrably the result of replacement of silica in the protore by hematite; that all of the large bodies have this origin cannot be proved, though it seems probable. Regional metamorphism and the relative lack in stability of silica and hematite under stress seem to have played a major role in this replacement, for many bodies occur at or near points of intense deformation. Hypogene solutions may also have been active.

SCIENTIFIC NOTES AND NEWS

The United Nations Scientific Conference on the Conservation and Utilization of Resources was held at the Interim Headquarters of the United Nations, Lake Success, N. Y., from August 17th to September 6th, 1949. Many geologists from all parts of the world attended the successful meetings. The Conference was devoted to an exchange of ideas and experience on the techniques of resource conservation and utilization, their economic costs and benefits and their inter-relations. The plenary meetings consisted of sections on the world resources situation, using and conserving resources, resource techniques of special interest to less-developed countries, experience in the inter-related application of resource techniques, while the section meetings dealt with all phases of mineral resources, fuels and energy, water, forests, land resources, wildlife, fish and marine resources.

T. B. NOLAN, Assistant Director of the U. S. Geological Survey, has returned to his office in Washington after two and a half months field work in Utah.

M. S. KRISHNAN, one of the Associate Editors of this Journal, was a delegate of India at the Lake Success Conference.

F. DIXEY, in charge of the Colonial Geological Surveys of the Imperial Institute, was in the United States during the summer attending the United Nations Conference and was making arrangements regarding a group of American geologists who are going to the various British Colonies Geological Surveys in Africa under an E.C.A. project.

SPENCER SHANNON has become Director of the Office of Materials in the Executive Office of the President, National Security Resources Board, 202 Old State Building, Washington, D. C.

MACK C. LAKE, mining engineer and geologist, has been appointed consulting engineer for the Oliver Iron Mining Co. and other U. S. Steel Corporation subsidiaries.

WARD CARITHERS, who had been working for the Chelan division of the Howe Sound Co. in Holden, Wash, is currently mining geologist for the Calera Mining Co., Forney, Idaho.

JOHN J. COLLINS, geologist with the U. S. Geological Survey, has taken up residence in Washington, D. C. at 2121 Virginia Avenue, N. W.

FORBES B. CRONK, after 44 years of continuous service, retired as general mining engineer of the Oliver Iron Mining Co. on July 1.

T. P. BILLINGS has become consulting mining engineer for the U. S. Smelting Refining and Mining Co. ARCH G. KIRKLAND succeeds him as manager of Western mines.

GEORGE C. HEIKES, formerly with the Kennecott Copper Corporation, has gone to Athens, Greece, with the ECA.

D. W. PHILLIPS has been appointed to the chair of mining at the New South Wales University of Technology, Broadway, Sydney, Australia.

H. A. QUINN has returned from West Africa and resumed his former post on the geological staff of Norman W. Byrne, consulting mining engineer, at Yellowknife, N. W. T.

FRANCIS F. REDFIELD has returned to the States from Aguilar, Argentina, and is now working as a mining engineer with the St. Joseph Lead Co.

PAUL M. TYLER is now in Europe studying ECA activities as part of his new position as minerals consultant for the Joint Congressional Committee on Foreign Economic Cooperation.

CLEAVES ROGERS has joined CARL FRIES, JR., and IVAN WILSON in Mexico, where the U. S. Geological Survey party is working in cooperation with the Instituto de Recursos Minerales.

At the request of the Thailand Government, the Department of State has sponsored a geological mission to that country for a period of approximately 6 months. Glen F. Brown and George C. Taylor, Jr., of the U. S. Geological Survey, arrived there in early October, and W. D. Johnston, Jr., will arrive in early January.

J. V. N. DORR II, of the U. S. Geological Survey, who has been studying the iron deposits of central Minas Geraes, Brazil, since 1947, in cooperation with the Departamento Nacional da Producao Mineral, arrived in the United States in late October for a period of home leave. He will return to Brazil in the spring. PHILIP W. GUILD, his associate in the iron studies, is expected to return to Washington in mid-1950.

The agreement between the Economic Cooperation Administration and the U. S. Geological Survey for furnishing geologists and topographers to work with various British Colonial Surveys was signed in early October. Further information can be obtained from the Chief, Alaskan and Foreign Geology Branch, Geological Survey, Washington.